Experimental Heavy-Ion Physics

High Energy Particle Physics Workshop 2015
University of the Witwatersrand, Johannesburg

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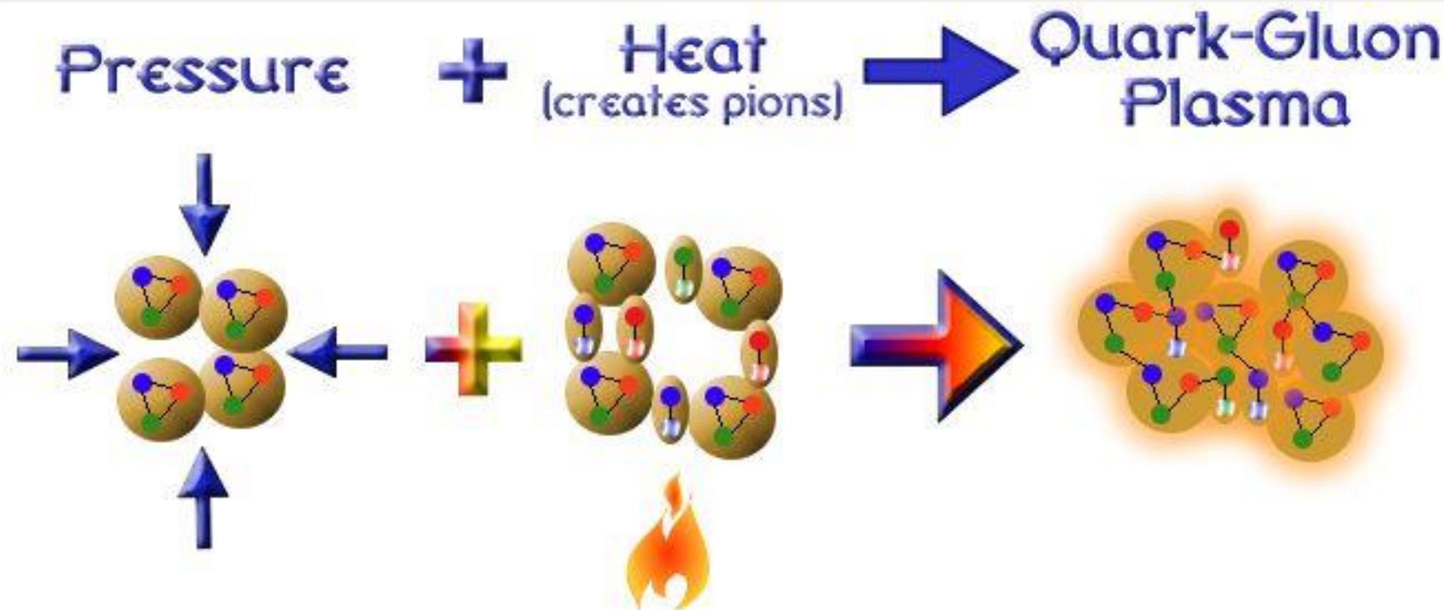
Outline

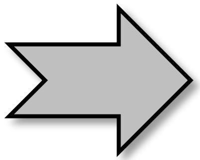
- Quark-Gluon Plasma and Heavy-Ion Collisions
- Flow and Collectivity
- Jet Quenching
- Heavy-Flavor Production
- Photons

Quark-Gluon Plasma



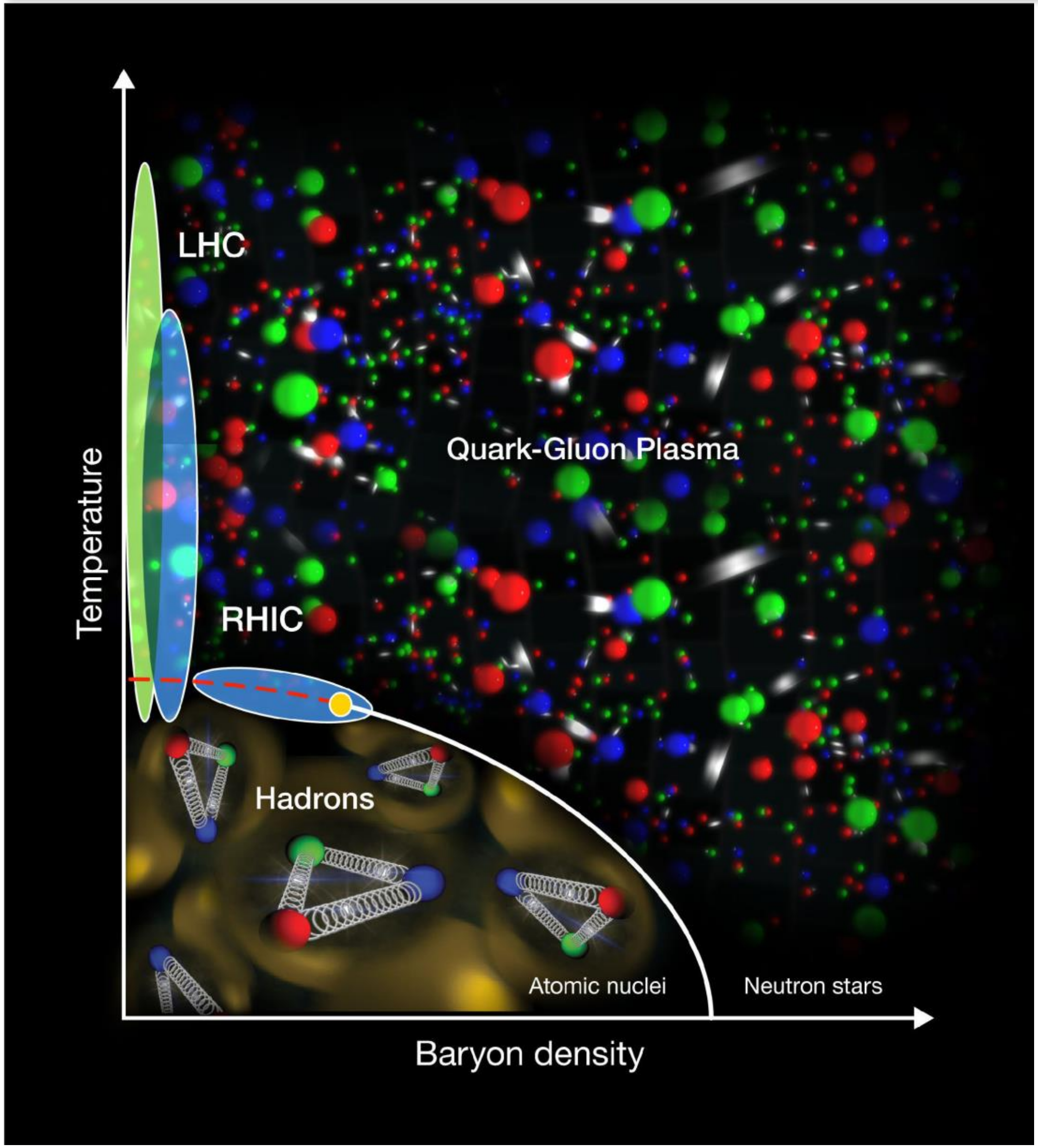
Compression
- reduce distance between nucleons

Heating
- thermally create pions
- fill space between nucleons



- hadrons overlap
- quarks roam freely over large volume (deconfinement)
- **Quark-Gluon Plasma**

Phase Diagram of Nuclear Matter

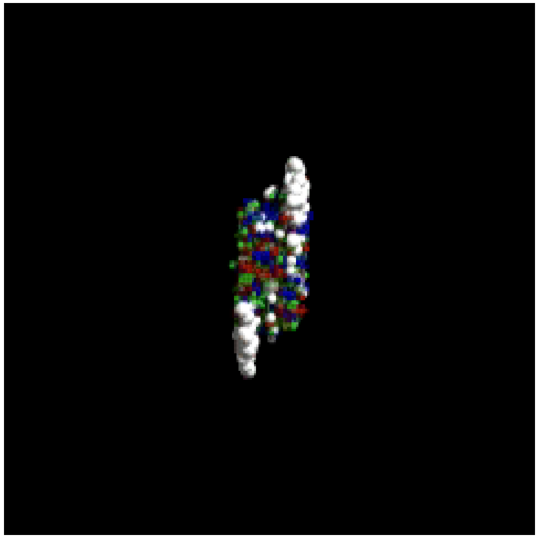


High density or high temperature → QGP

- phase transition at 170 MeV ≈ 2 trillion Kelvin

Accessible with accelerators: RHIC, LHC

Heavy-Ion Collisions

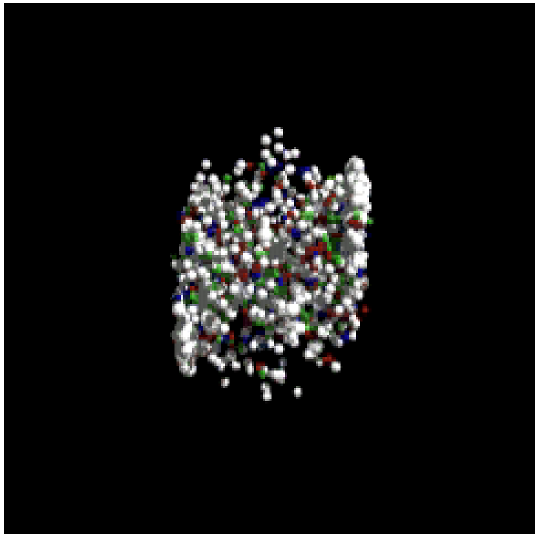


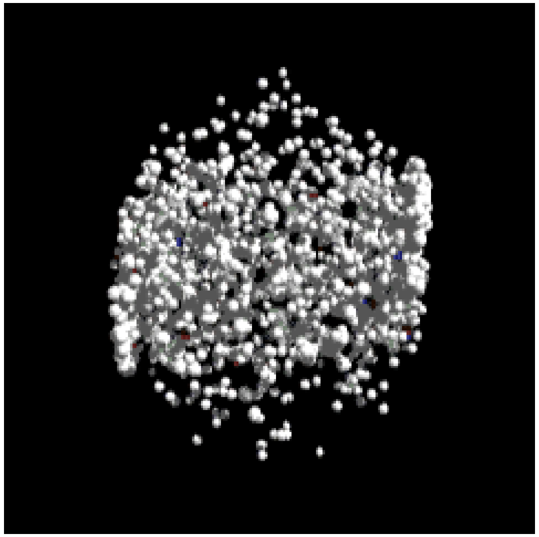
Collisions of Heavy Nuclei

- Pb-Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV

Quark-Gluon Plasma

- deconfined phase of quasi-free quarks and gluons
- LHC–highest energy HI collisions
  - hottest and longest lived QGP
  - ideal environment





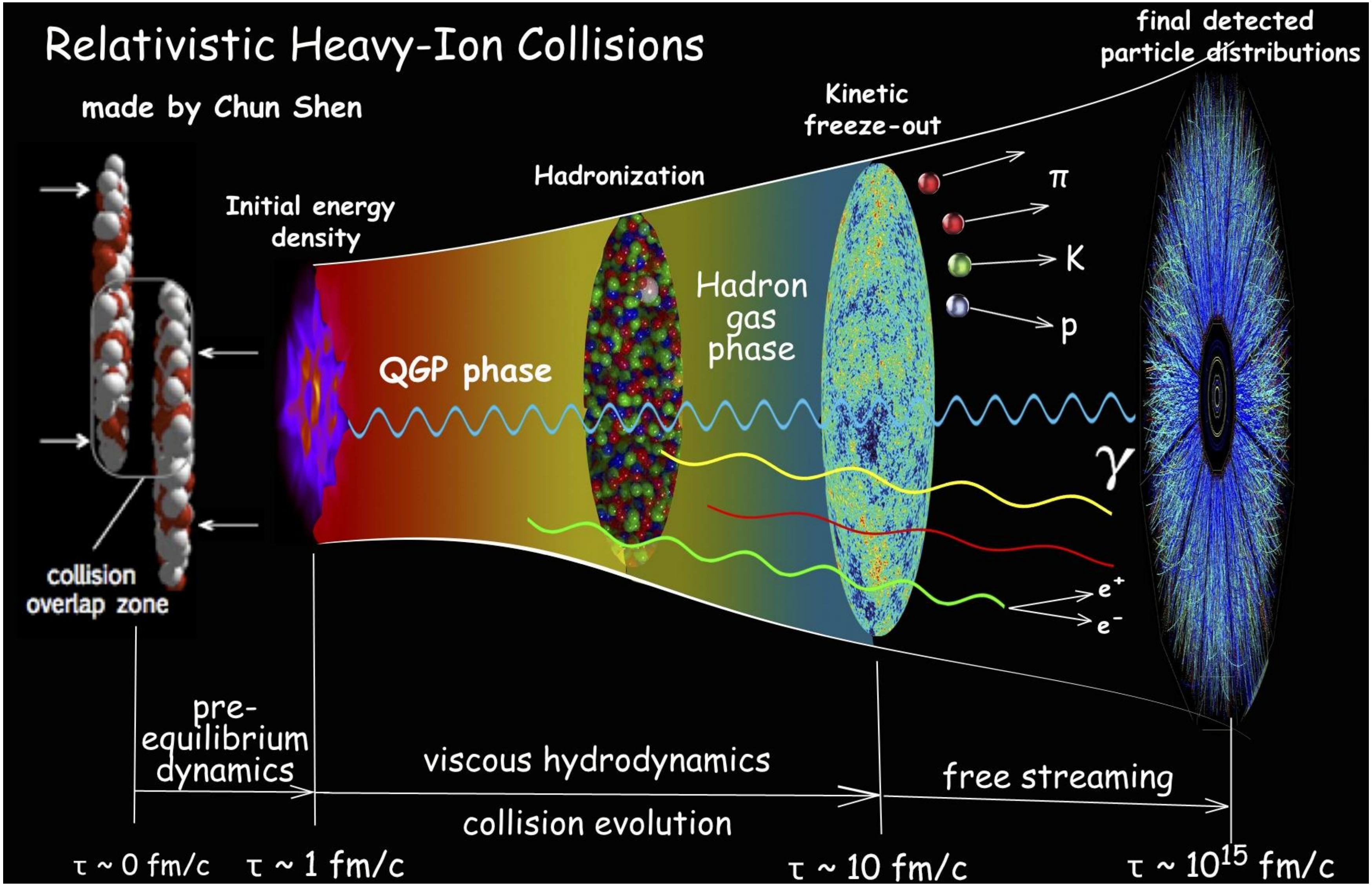
Hadronisation

- fragmentation and quark coalescence produce hadrons
- formed after end of QGP phase
- thousands of particles

Photons

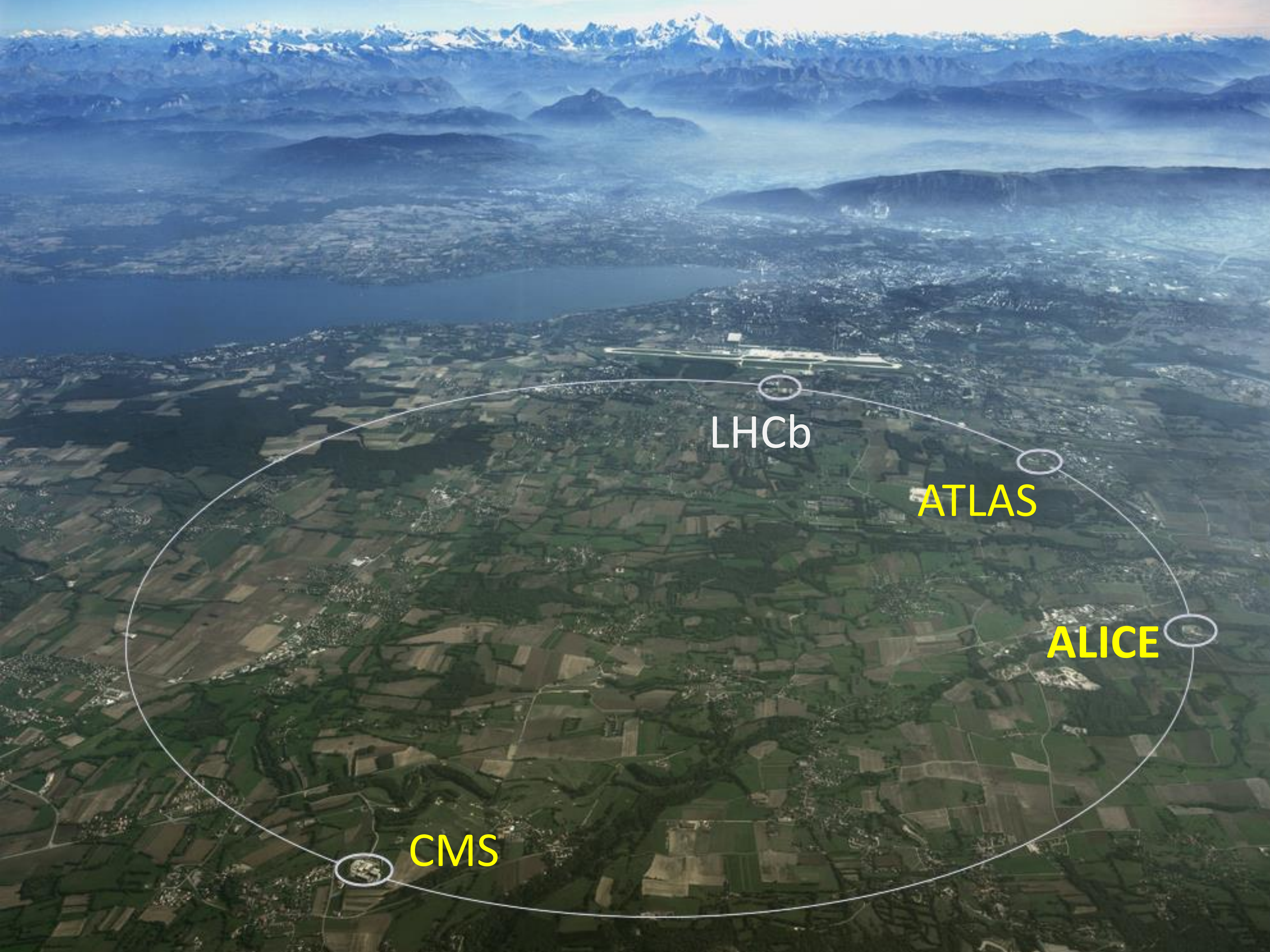
- no final state interaction
- direct signal from all phases of collision

The Little Bang



Relativistic Heavy Ion Collider

since 2000
Au-Au @ $\sqrt{s_{nn}}$ 200 GeV
Brookhaven National Lab
Long Island, NY, USA

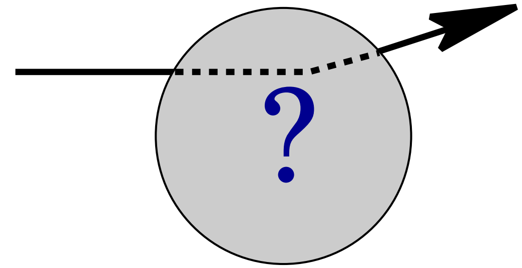


LHCb
ATLAS
ALICE
CMS

Probing the QGP

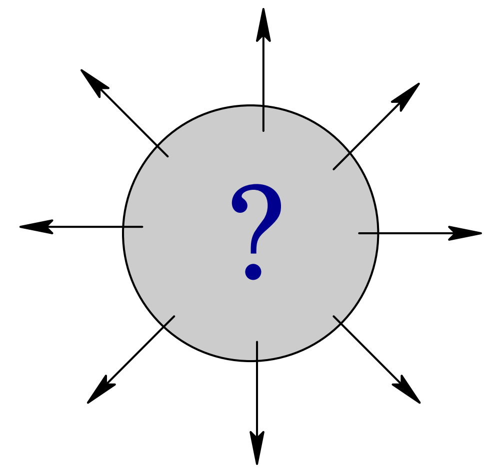
scattering experiments

- external illumination
- not possible



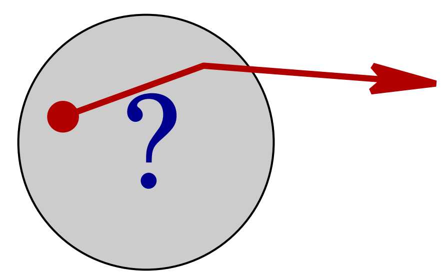
bulk: products from the medium

- QGP expands, cools down, hadronises
- particle species, spectra, flow

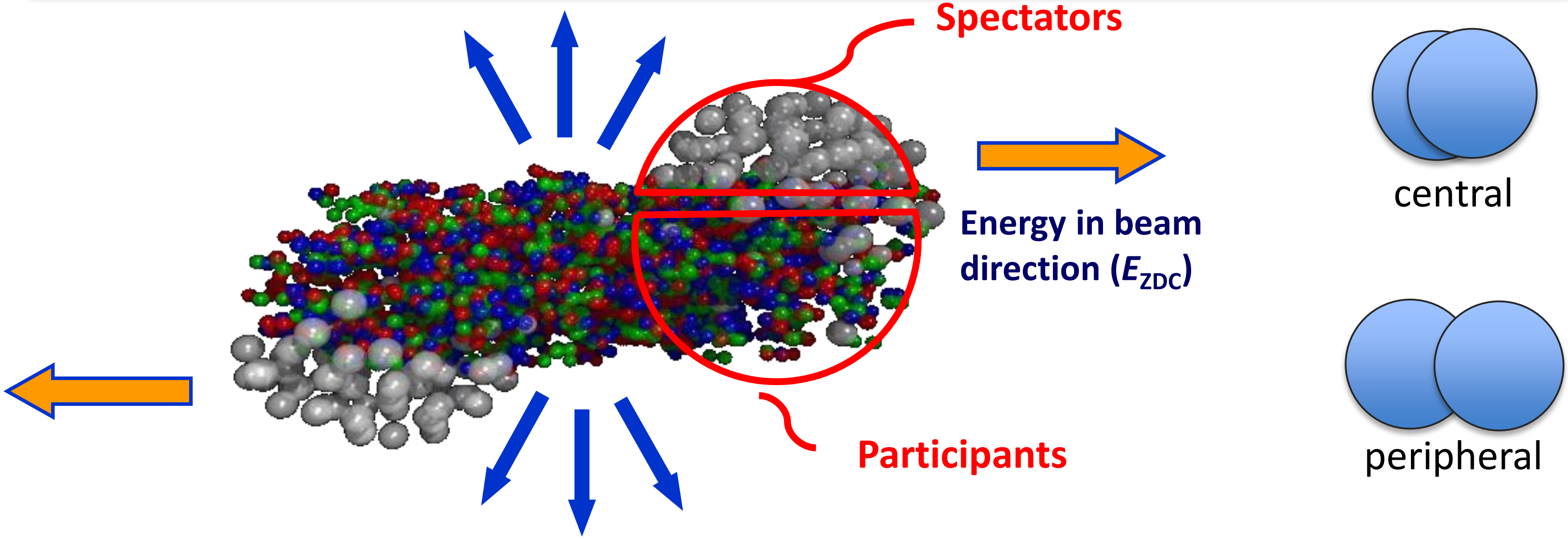


hard probes

- production in collisions
- rare → traceable
- interaction with medium
- energetic quarks → jets, quarkonia



Centrality



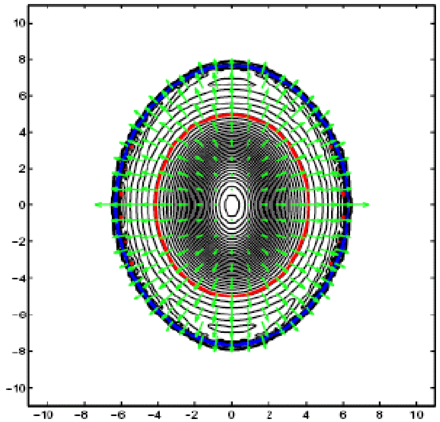
central collisions: small impact parameter, many participants, many collisions between participants

peripheral collisions: large impact parameter, few participants, mostly spectators

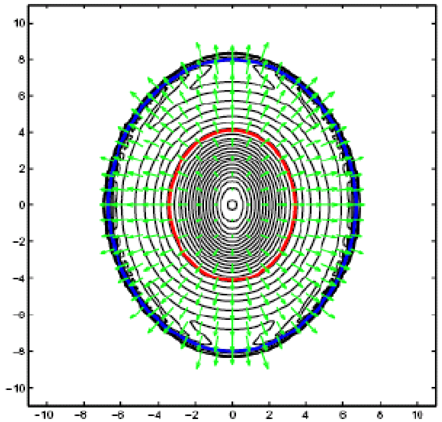
system size

- b: impact parameter
- N_{part}: number of participants
- N_{coll}: number of nucleon-nucleon collision
- percentile of total cross section, e.g. 0-5% most central collisions

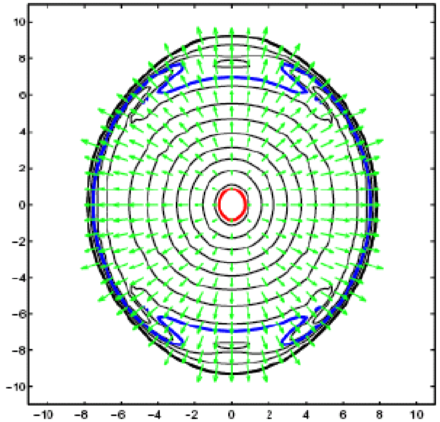
Relativistic Hydrodynamics



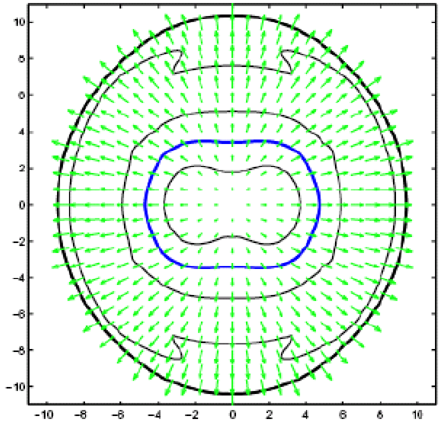
3.2 fm/c ($\epsilon_x = 0.160$, $\epsilon_p = 0.114$)



4.0 fm/c ($\epsilon_x = 0.127$, $\epsilon_p = 0.141$)



5.6 fm/c ($\epsilon_x = 0.067$, $\epsilon_p = 0.147$)



8.0 fm/c ($\epsilon_x = 0.003$, $\epsilon_p = 0.123$)

Initial Conditions

- geometry and density in collision region
- Glauber vs. Gluon Saturation (e.g Color-Glass Condensate CGC)
- thermalization time T0

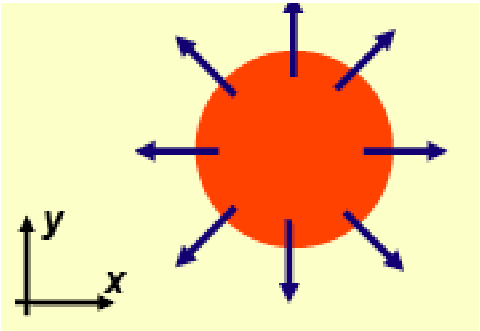
Medium Properties

- equation of state (EOS)
  - QGP or hadron gas
- viscosity η
- mean free path λ

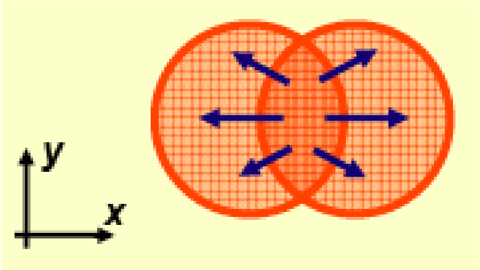
Relativistic Euler Equation

- evolution of density and motion with time

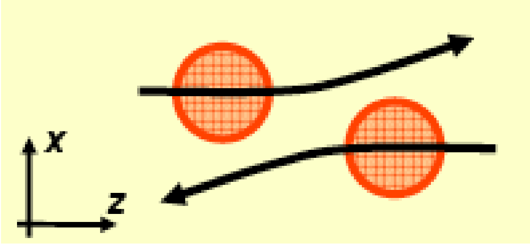
Collectivity



- Radial flow
  - Only type of transverse flow that occurs also at impact parameter $b = 0$
  - Influences the shape of p_T spectra (transverse expansion)

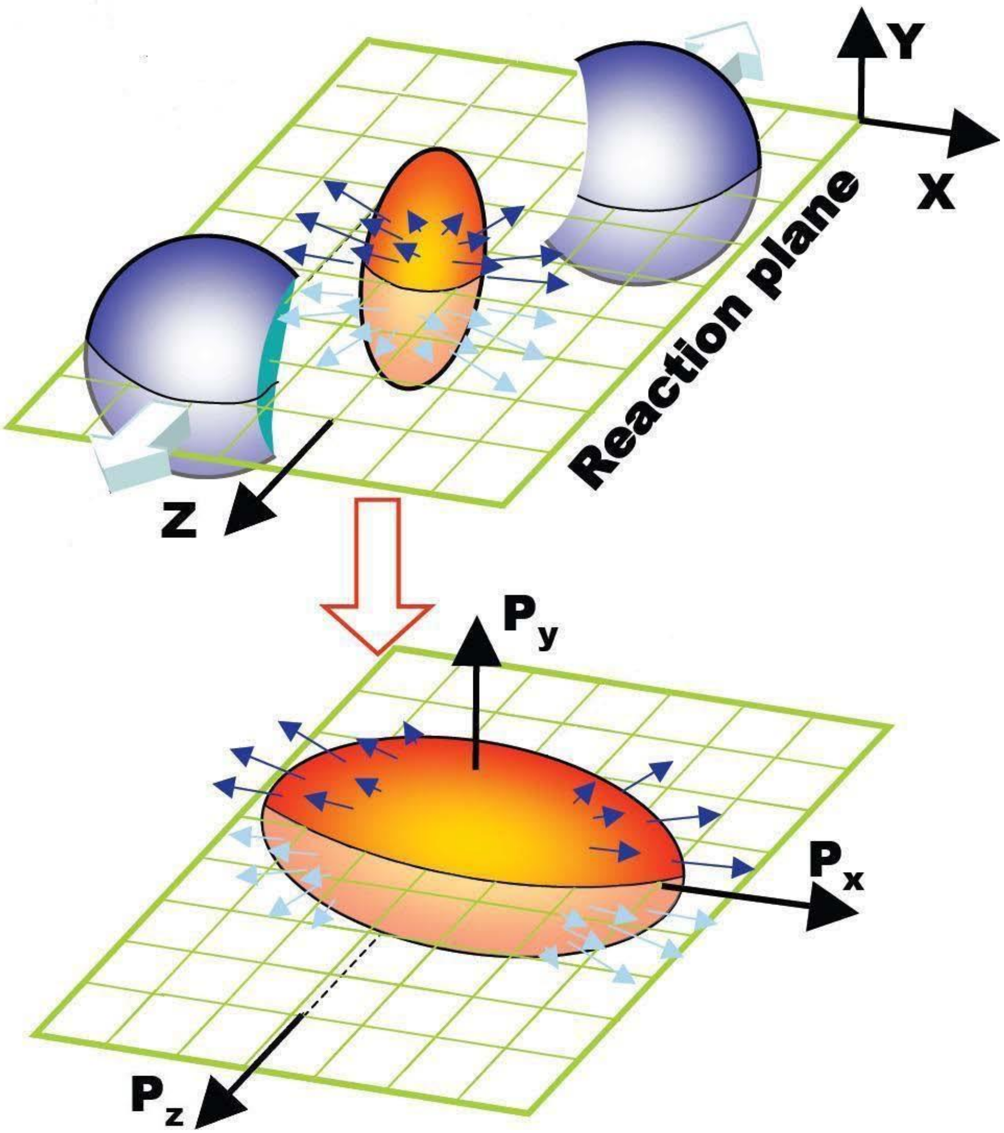


- Elliptic flow
  - Caused by anisotropy in overlap region for $b \neq 0$ (pressure gradient)
  - Needs early thermalization



- Directed flow
  - Built up during pre-equilibrium phase
  - Decreases with increasing CMS energy

Elliptic Flow



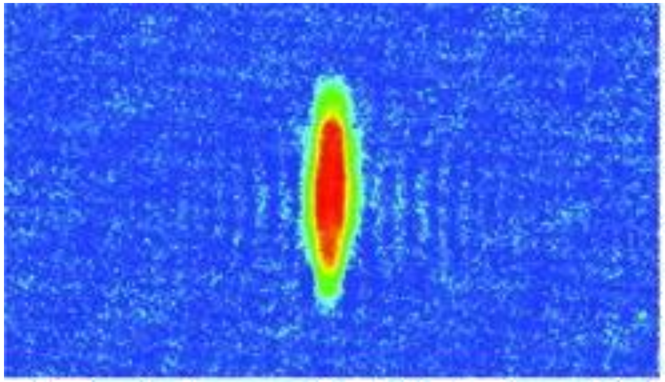
- Anisotropy (almond shape) in the overlap region translates in anisotropy in the momentum distribution
- Caused by different pressure gradients in and out of the reaction plane

$$\frac{\mathrm{d}P_x}{\mathrm{d}x} > \frac{\mathrm{d}P_y}{\mathrm{d}y}$$

- Needs:
  - Early thermalisation
  - Strong coupling

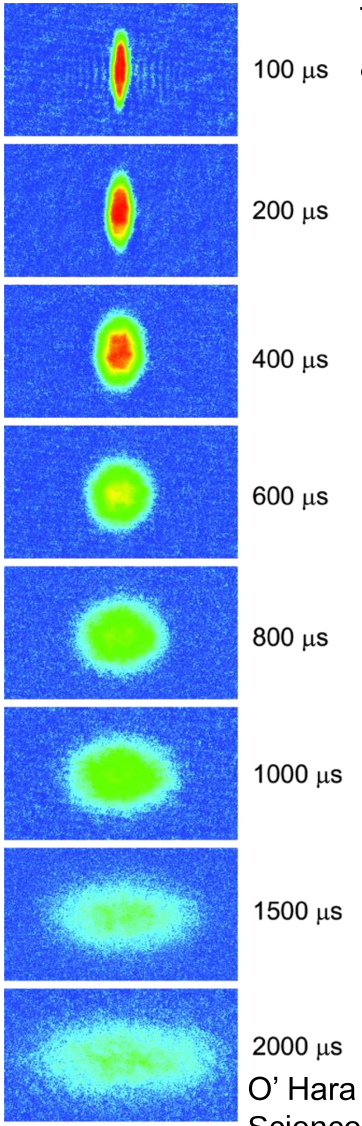
Analogy: Strongly Coupled Atoms

Cold atomic gas (^{6}Li, $T = 10^{-6}$ K)



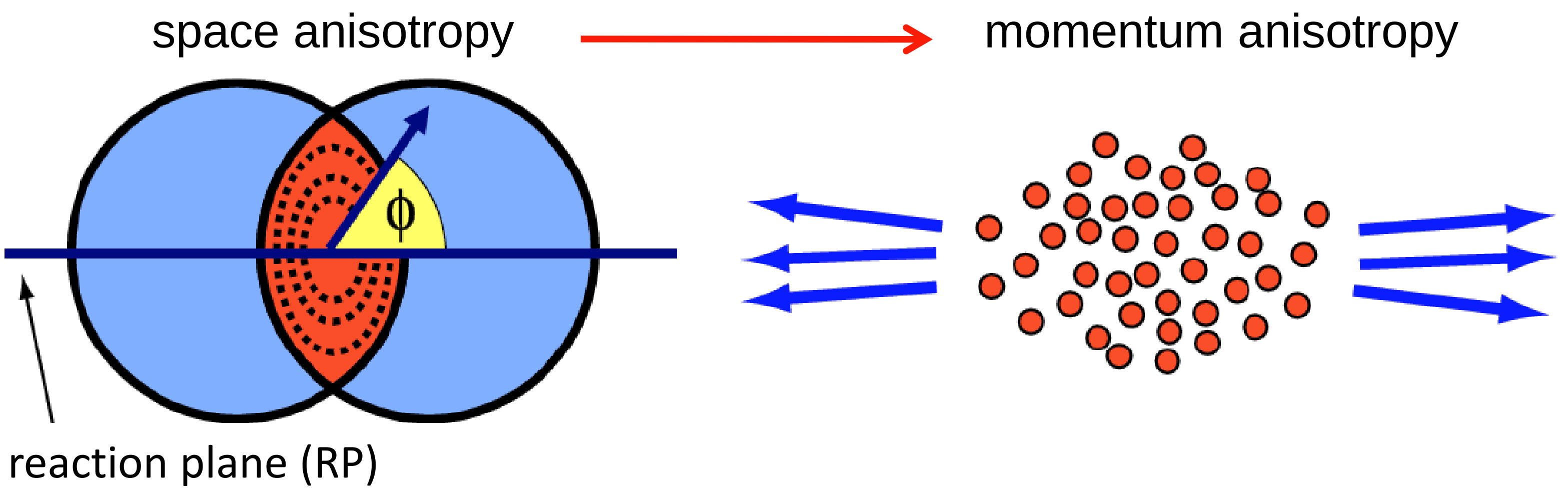
- Tuneable coupling (Feshbach resonance)
- Weak coupling: No momentum anisotropy
- Strong coupling: Collective elliptic flow

Time after releasing atoms from trap



O' Hara et. al
Science 298 (2002) 5601

Fourier Expansion



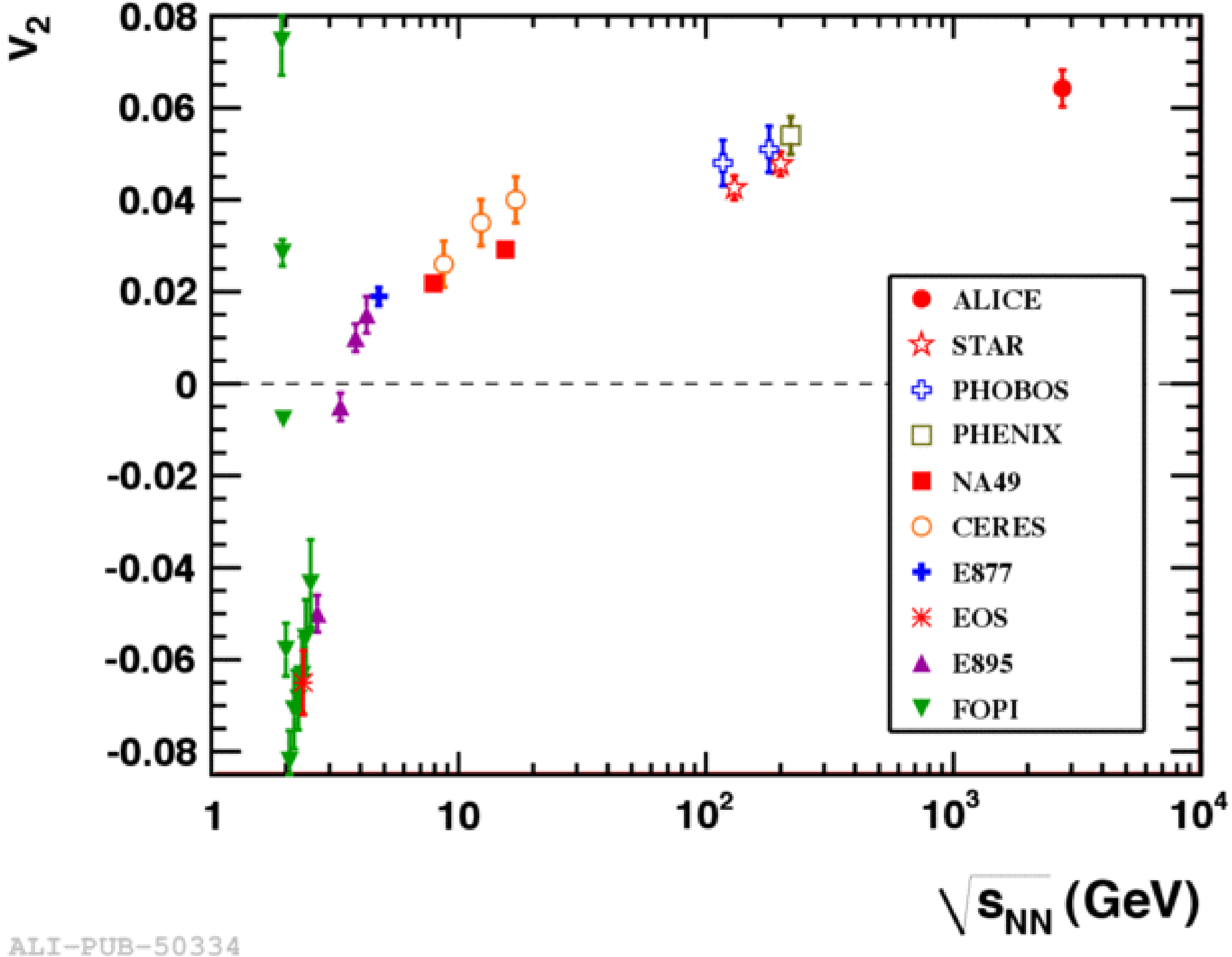
Fourier expansion of the particle distribution with respect to the reaction plane ($\phi = \phi_{\text{particle}} - \phi_{RP}$)

$$\frac{\mathrm{d}^2 N}{\mathrm{d}\phi\,\mathrm{d}p_T} = N_0\left(1 + 2v_1\cos\phi + 2v_2\cos\phi + \ldots\right)$$

v_1: Magnitude of directed flow (vanishes at mid-rapidity)
v_2: Magnitude of elliptic flow

Integrated Elliptic Flow

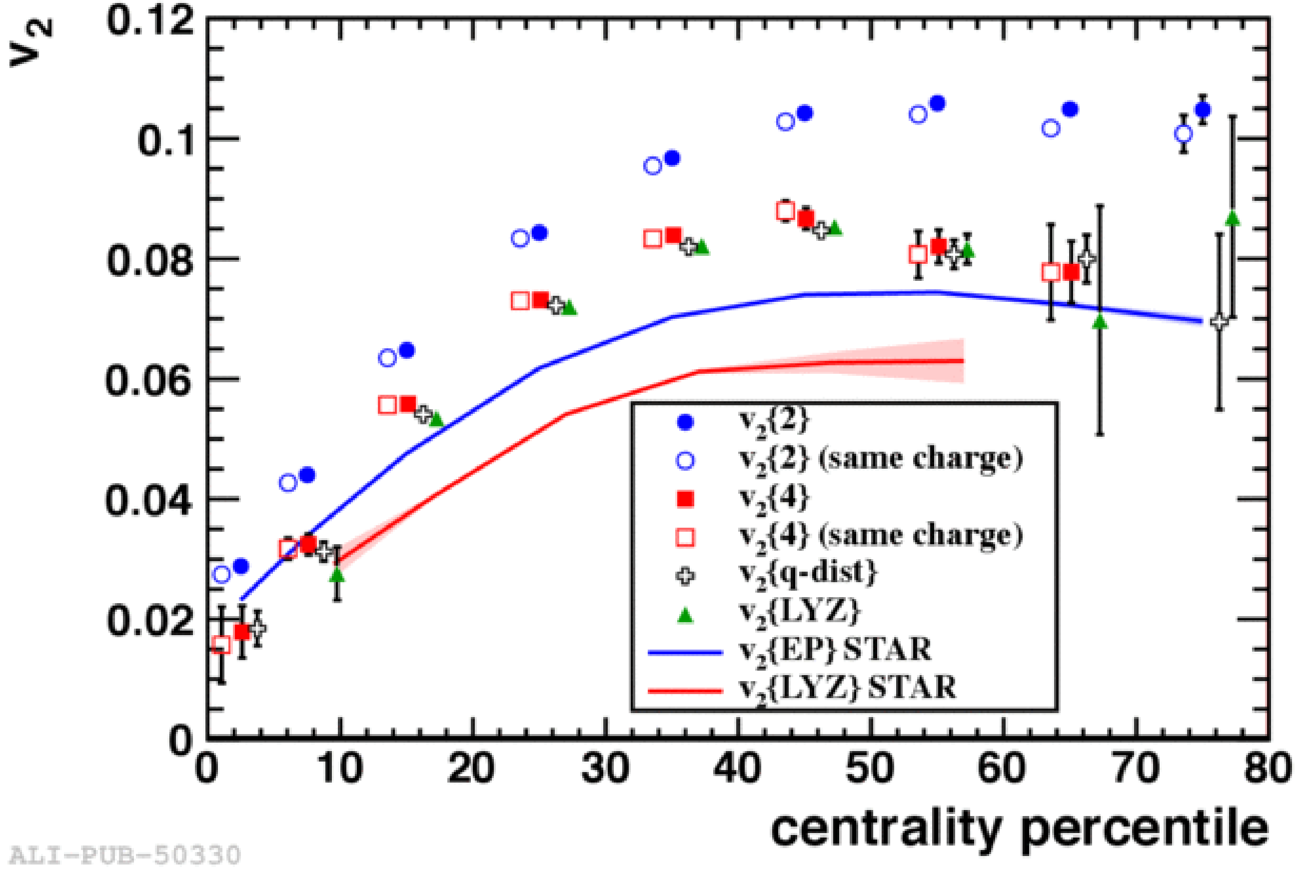
Phys. Rev. Lett. 105, 252302 (2010)



Increasing elliptic flow from SPS via RHIC to LHC

Centrality Dependence

Phys. Rev. Lett. 105, 252302 (2010)

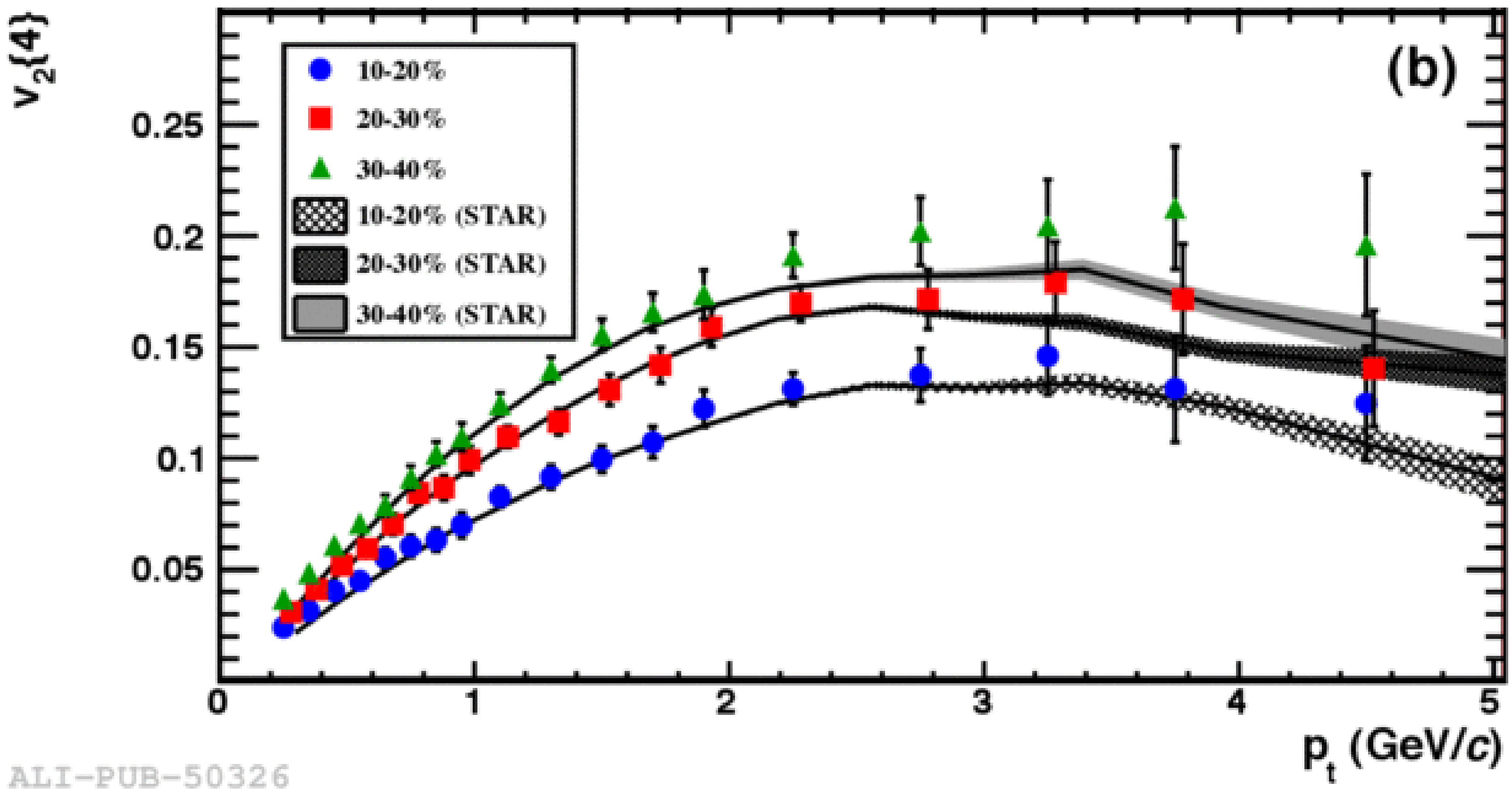


Largest elliptic flow for (semi-)peripheral collisions

Central collisions have small initial anisotropy

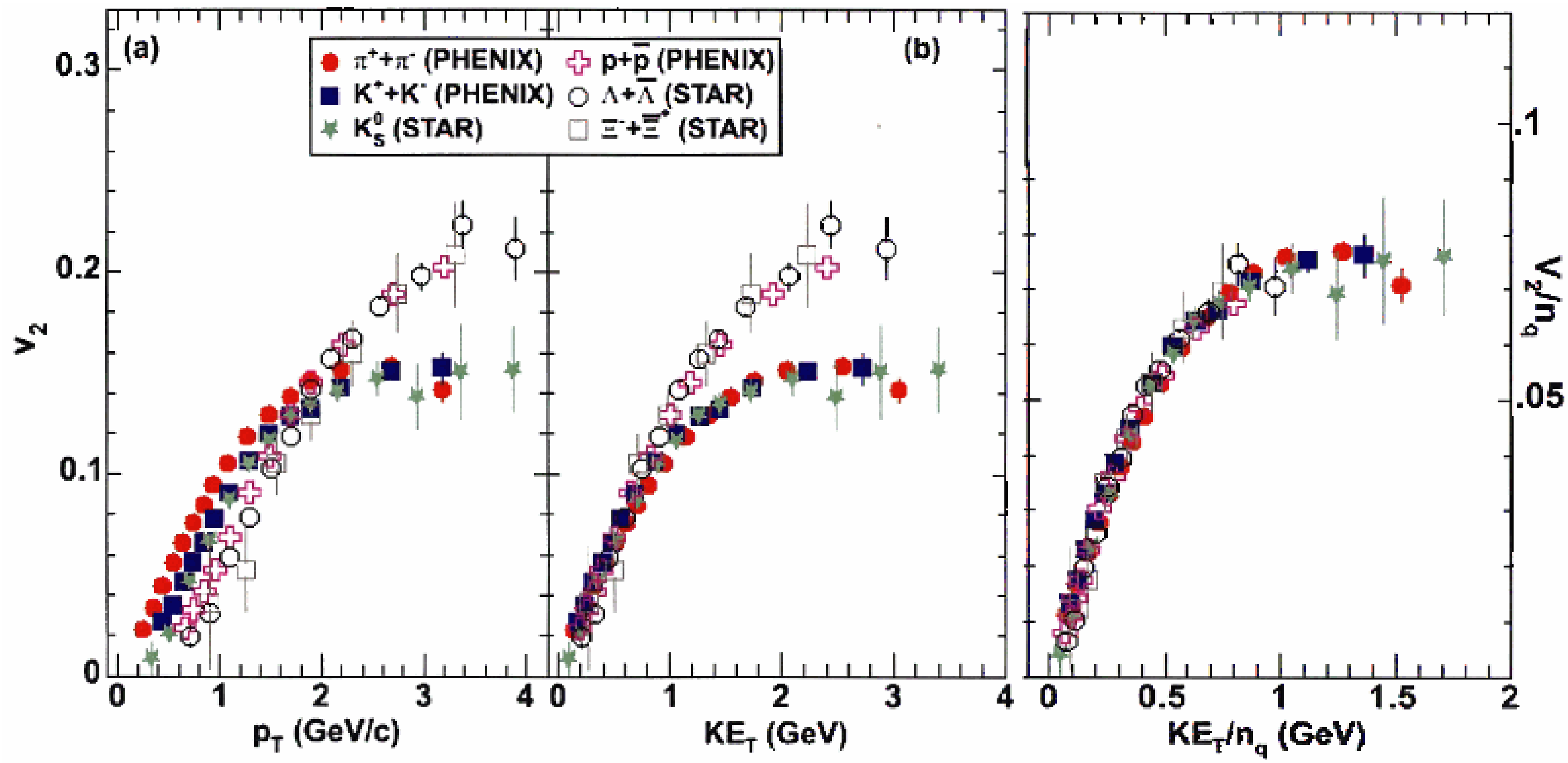
Elliptic Flow

Phys. Rev. Lett. 105, 252302 (2010)



$v_2(p_T)$ similar at STAR / RHIC and ALICE / LHC

Identified Particle v2 at RHIC



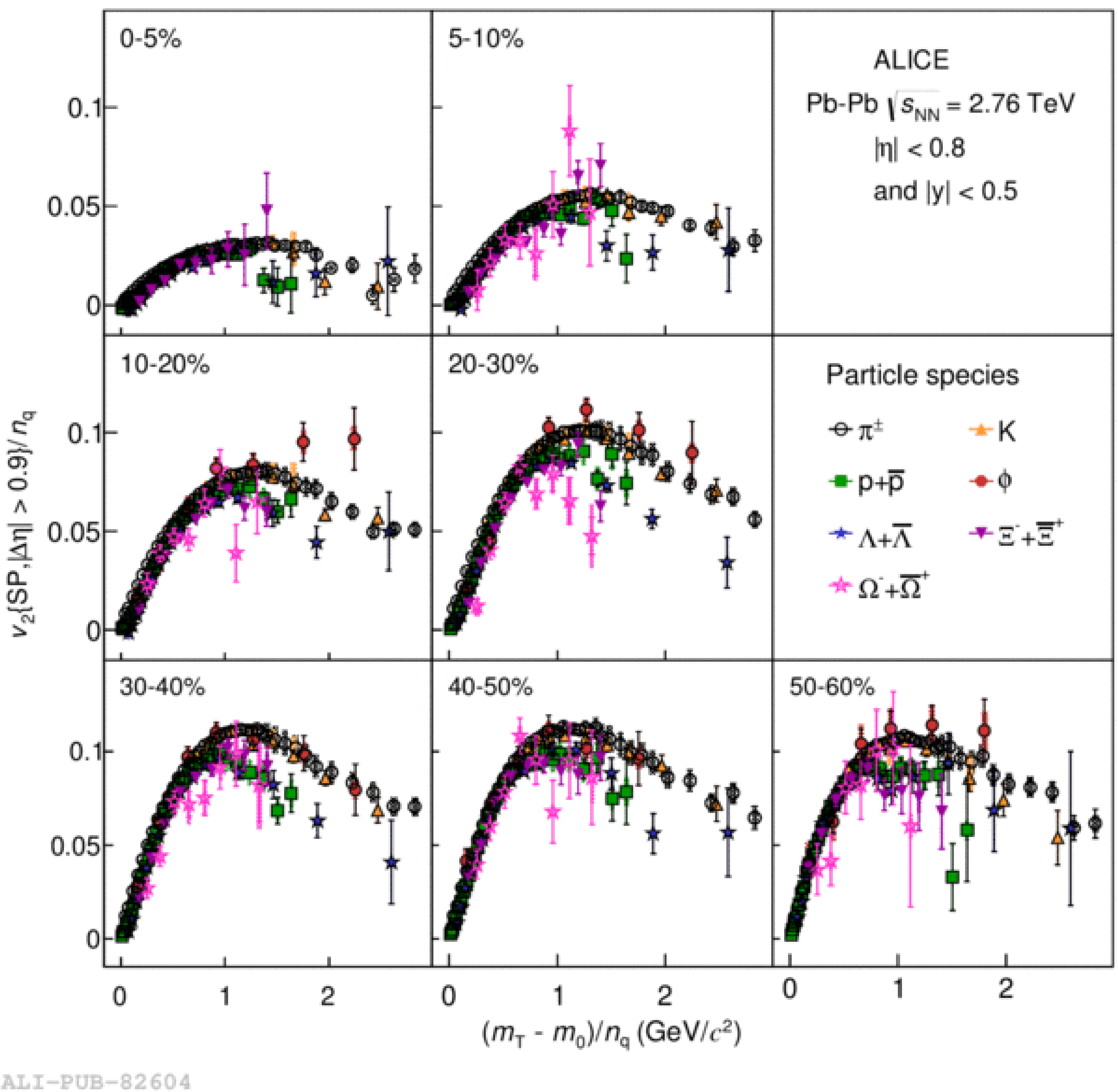
- v2(pT) driven by radial and elliptic flow
- kinetic transverse energy $KE_T = m_T - m$ removes mass bias
- perfect constituent quark scaling (NCQ)

Identified particle v_2 at LHC

arXiv:1405.4632 [nucl-ex]

NCQ scaling only approximate at LHC

Concidence at RHIC?



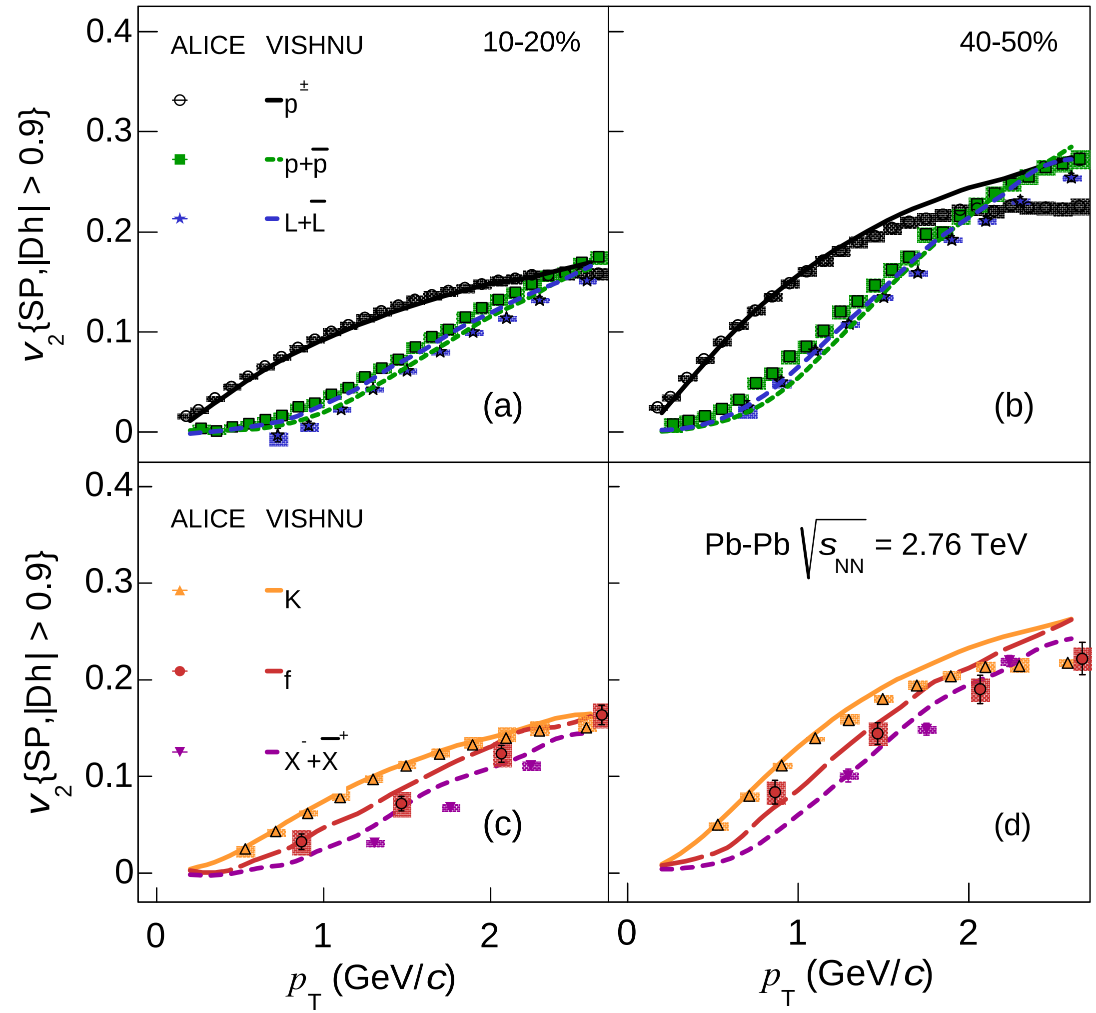
Comparison with Hydro Models

arXiv:1405.4632 [nucl-ex]

VISHNU: hydro + hadronic cascade

- good agreement for π, K, ϕ
- disagreement for p, Λ, Ξ

Precision data and models needed!



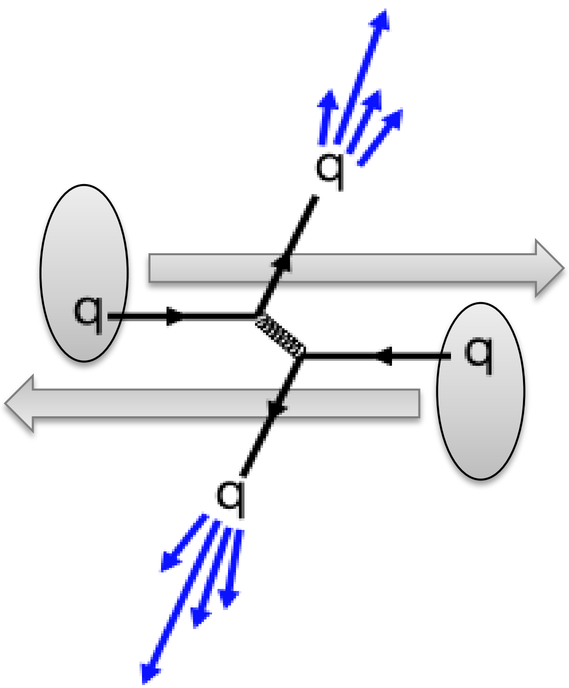
Hard Processes – Jets

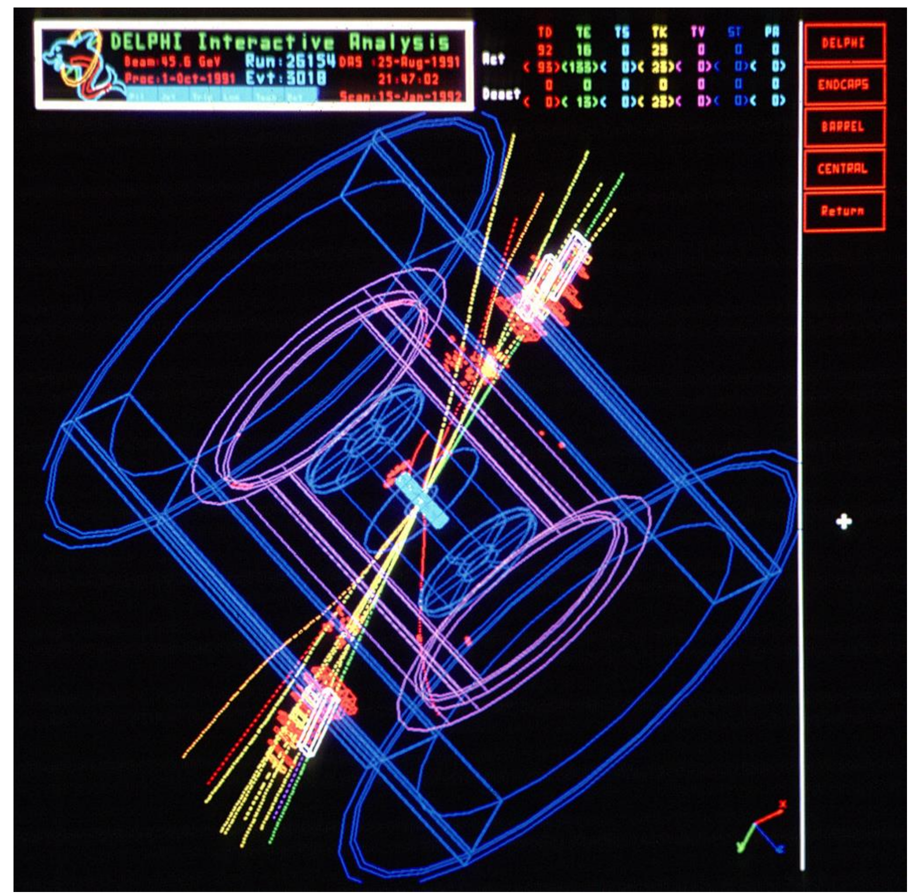
Parton collisions (q-q, q-g, g-g)

- small cross section for high momentum transfer →high p_T partons

Fragmentation

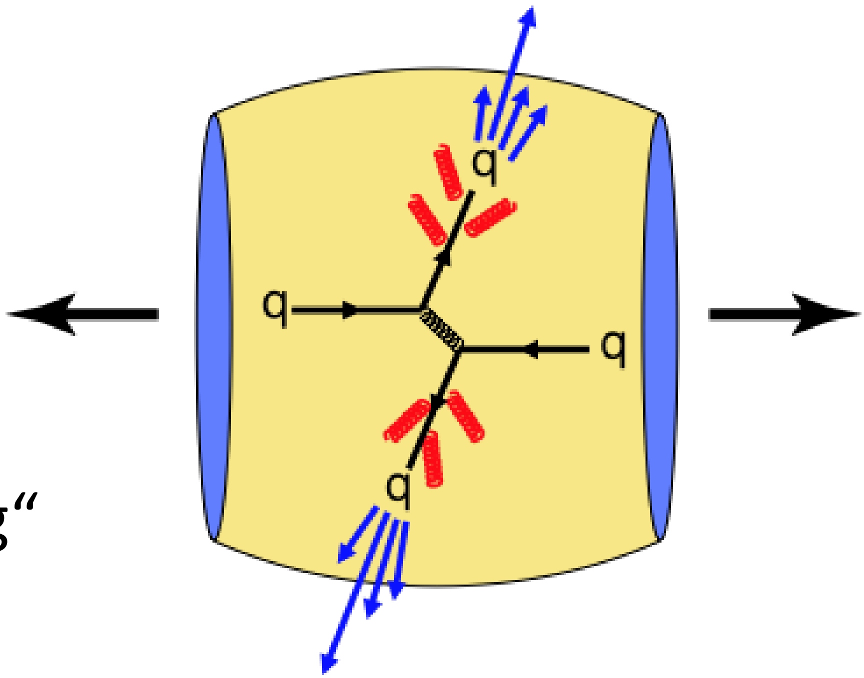
- bunches of hadrons from parton → jet of particles



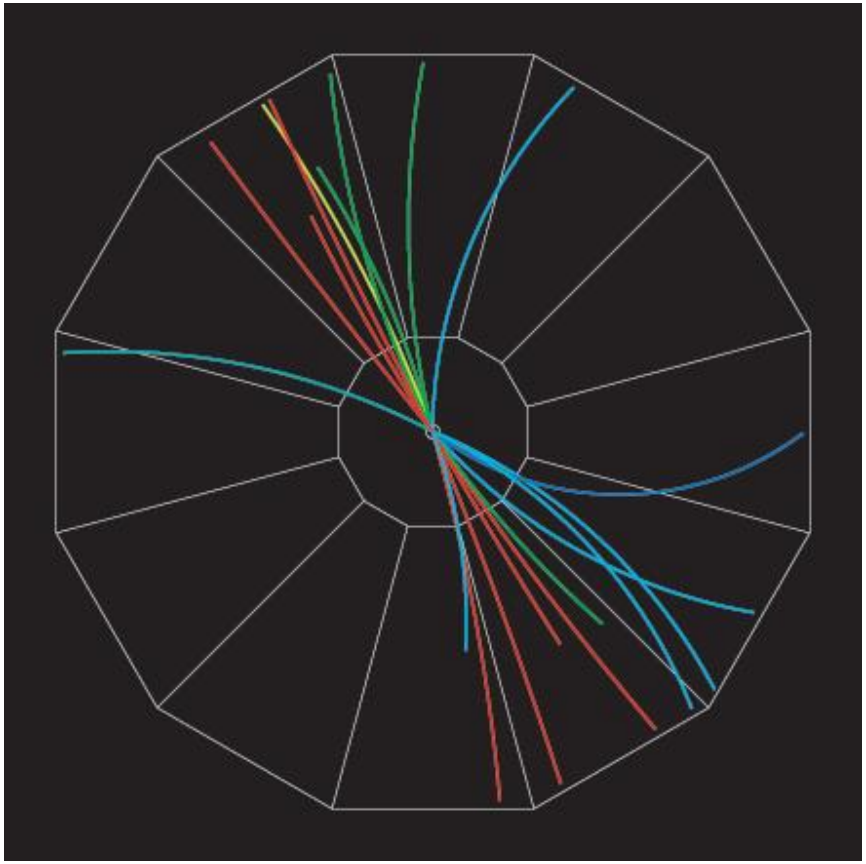


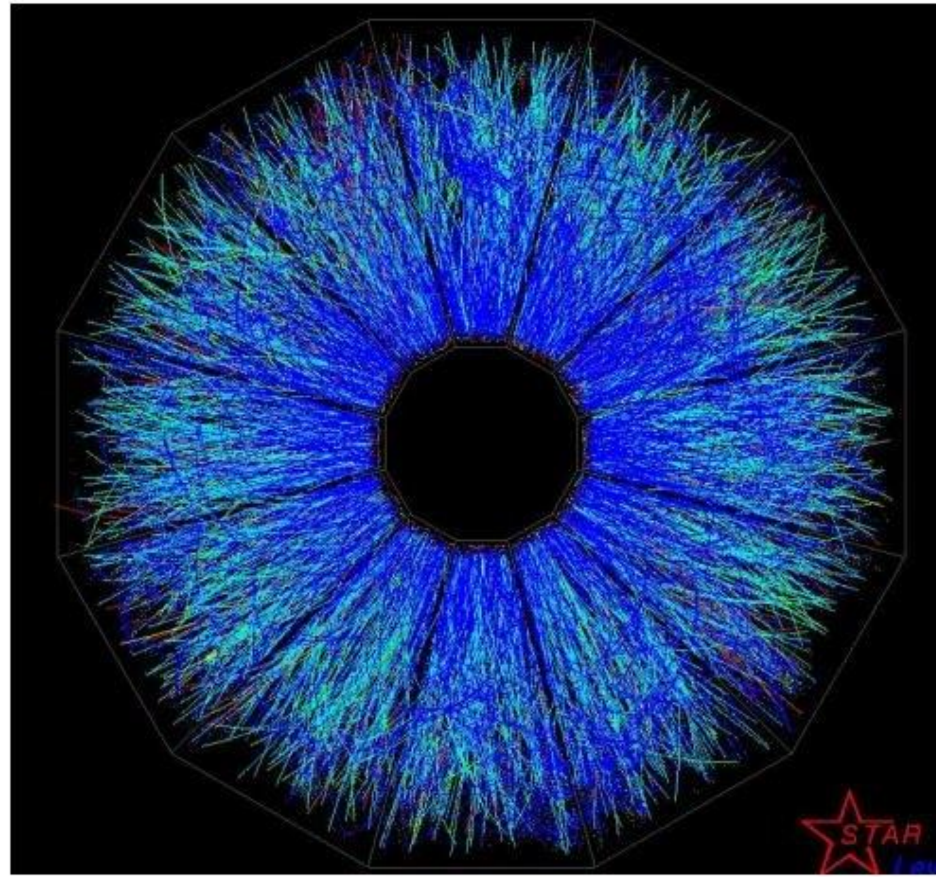
Jets Quenching

- hard production process
  - well understood in pQCD
- propagation in medium
  - gluon-Bremsstrahlung
  - collisions with partons
  - energy loss – „jet quenching“
- jet modifications carry information about parton-medium interaction
  → **probe of the medium**



Jets in Heavy Ion Collisions



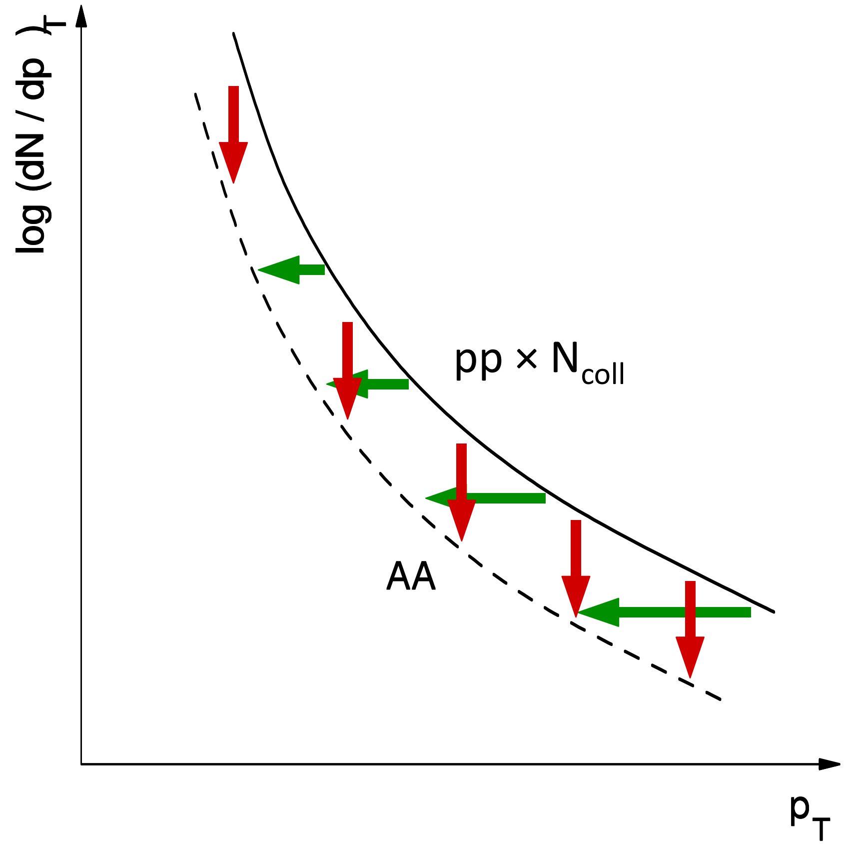


High p_T Hadron Suppression

Nuclear Modification Factor

- ratio of *single* particle production in AA and pp collisions
- normalized with N_{coll}: number of nucleon-nucleon collisions

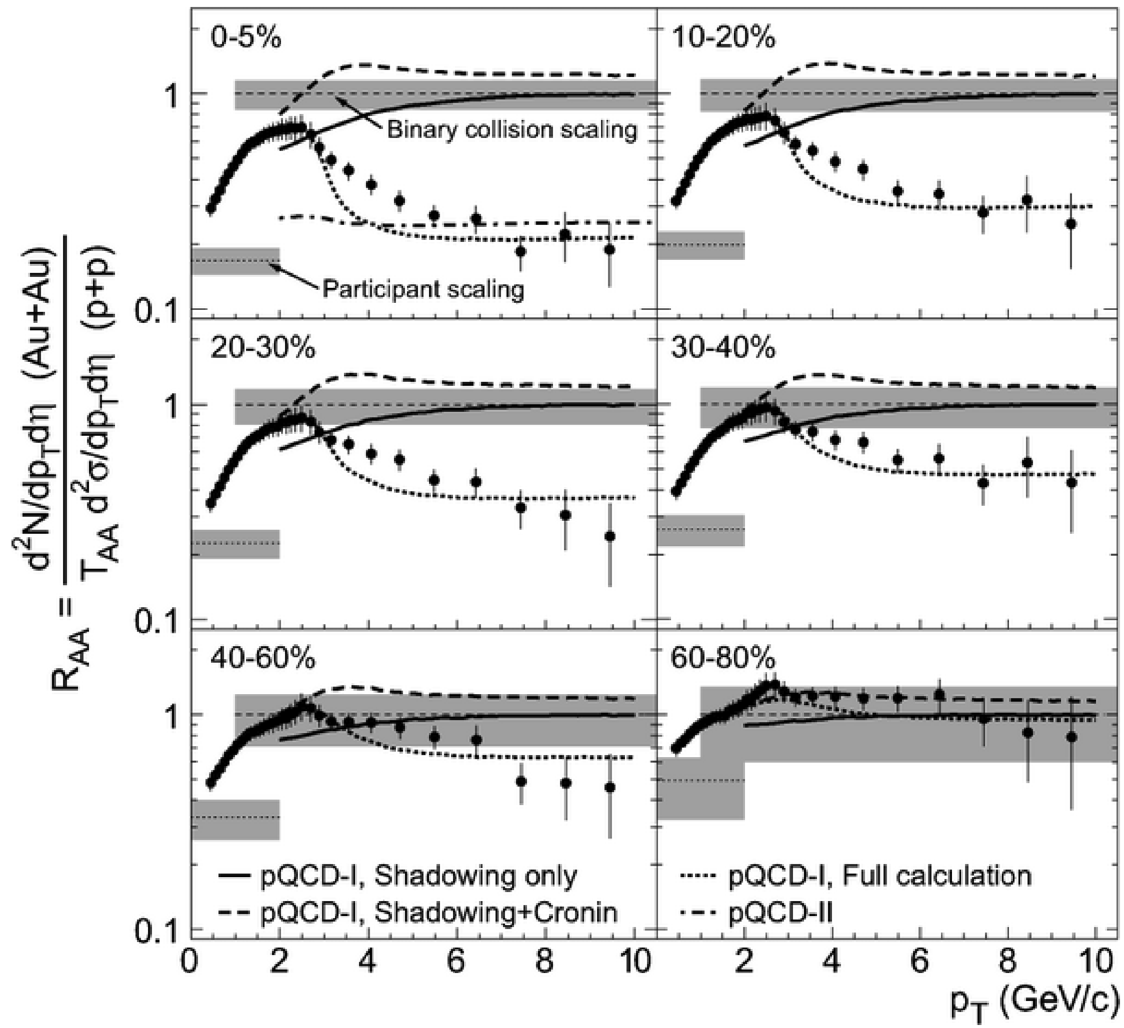
$$R_{AA} = \frac{1}{N_{coll}} \frac{dN_{AA}/d\eta dp_T}{dN_{pp}/d\eta dp_T}$$



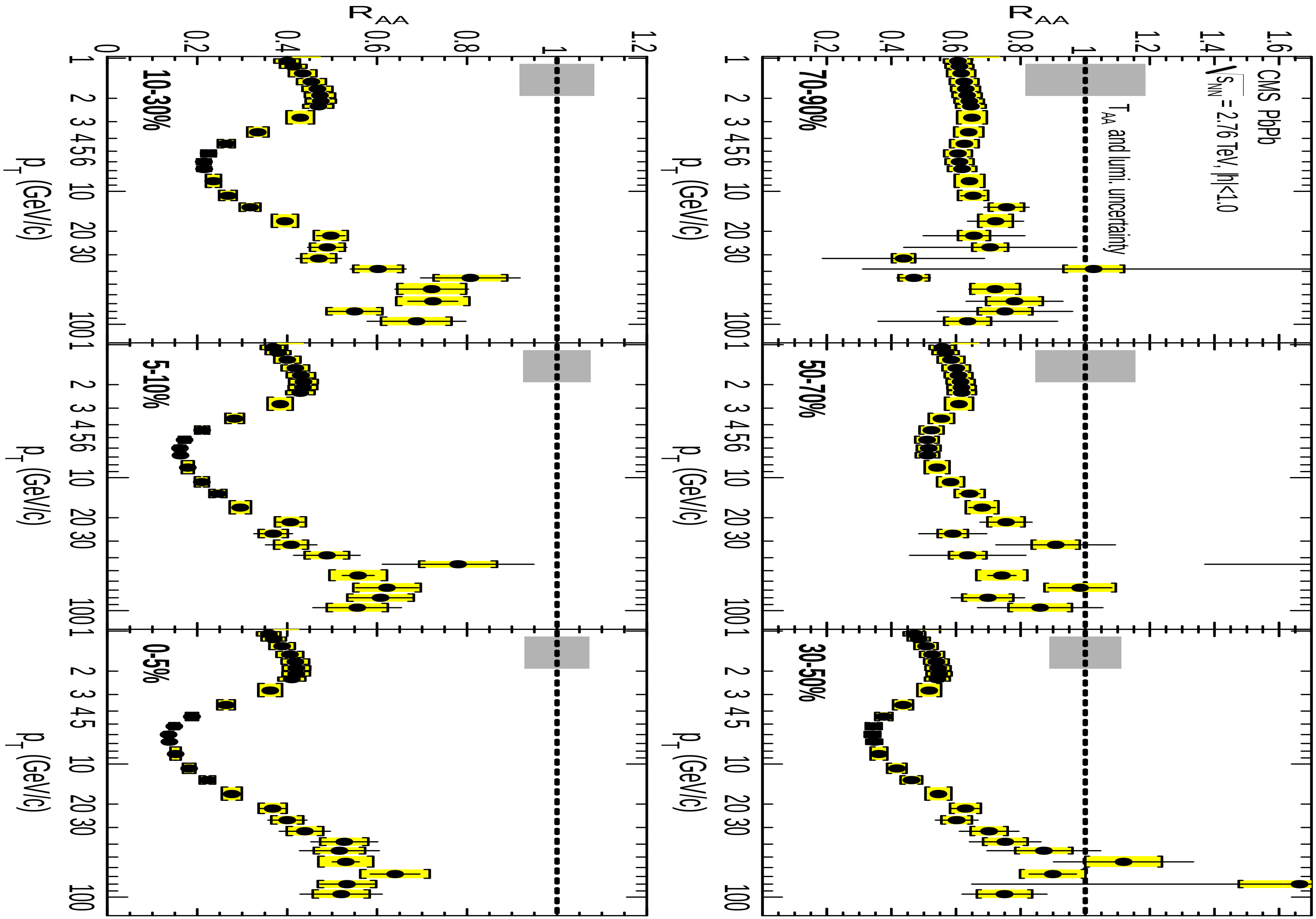
R_{AA} by STAR @ RHIC

- no modification in peripheral collisions
- strong suppression (factor 5) in central collisions
- smooth transition from peripheral to central

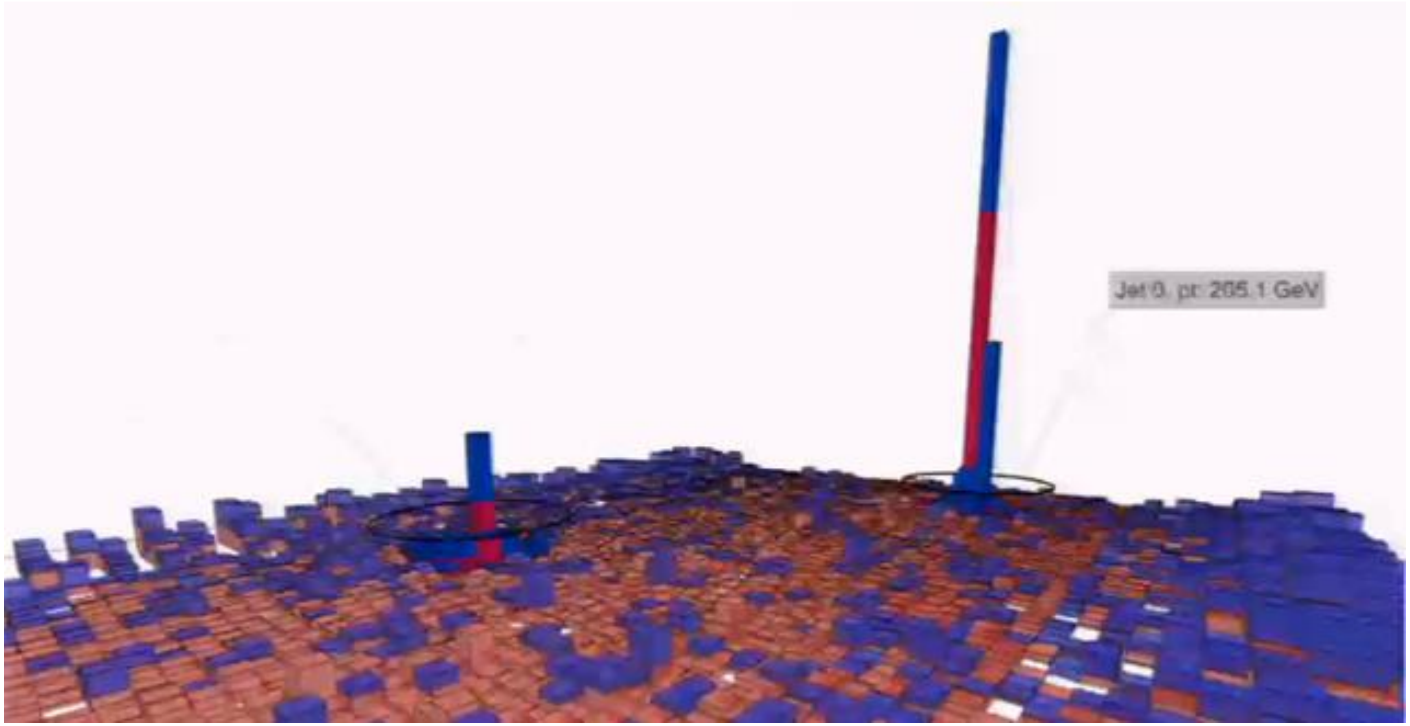
consistent with parton energy loss



R_{AA} by CMS


CMS PbPb
$\sqrt{s_{NN}}$ = 2.76 TeV, |η|<1.0
T_{AA} and lumi. uncertainty
70-90%
50-70%
30-50%
10-30%
5-10%
0-5%
R_{AA}
p_T (GeV/c)

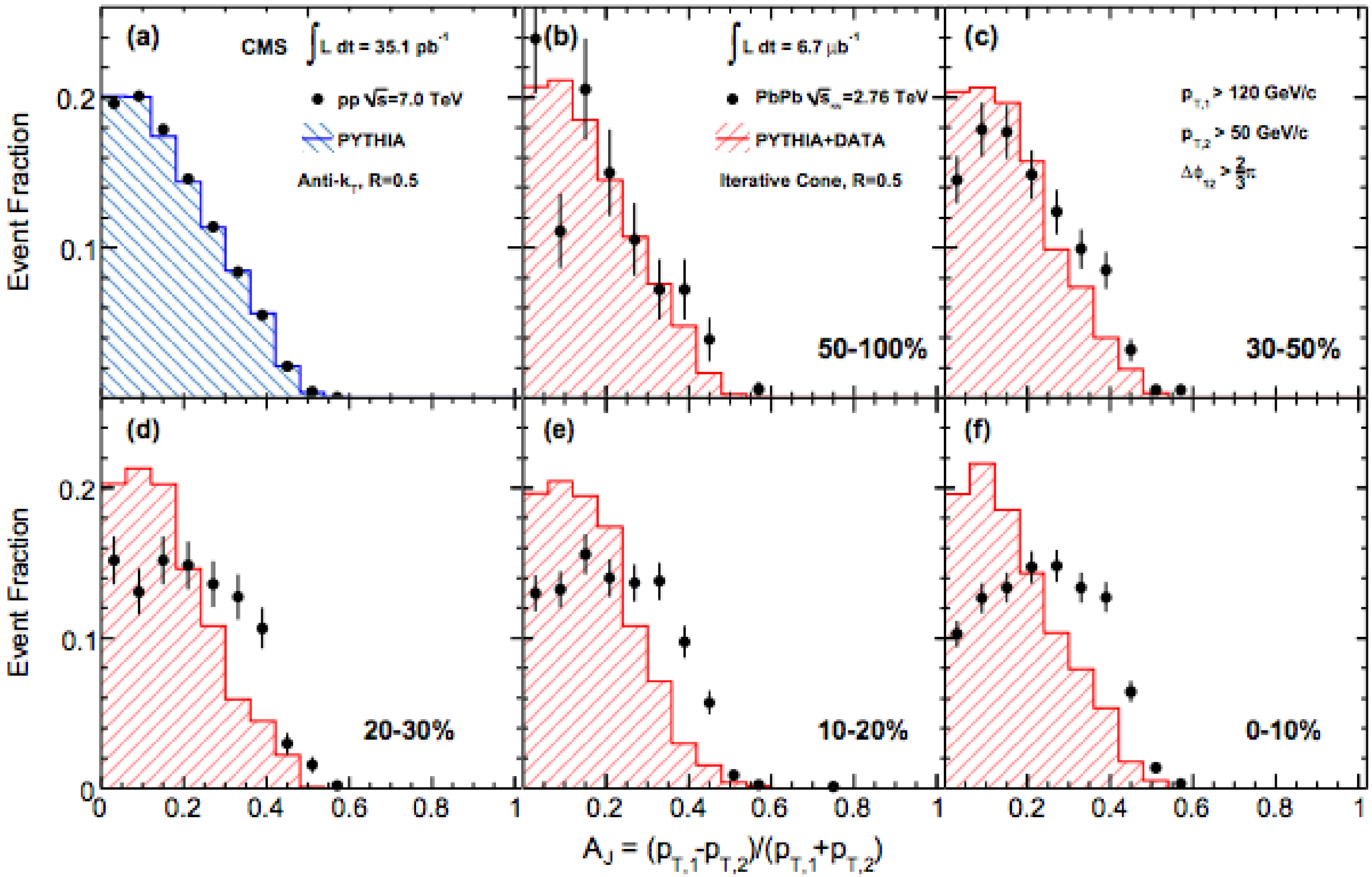
Asymmetric Di-Jets



- di-jets in pp are created (almost) balanced
- energy loss of one jet can lead to momentum imbalance
- study via di-jet imbalace:

$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

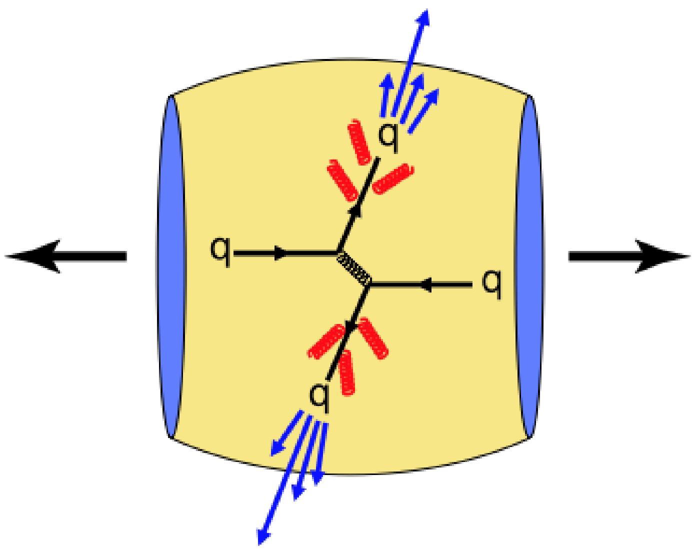
Di-Jet Imbalance



- largest asymmetry in central AA
- evidence for quenching of at least one jet

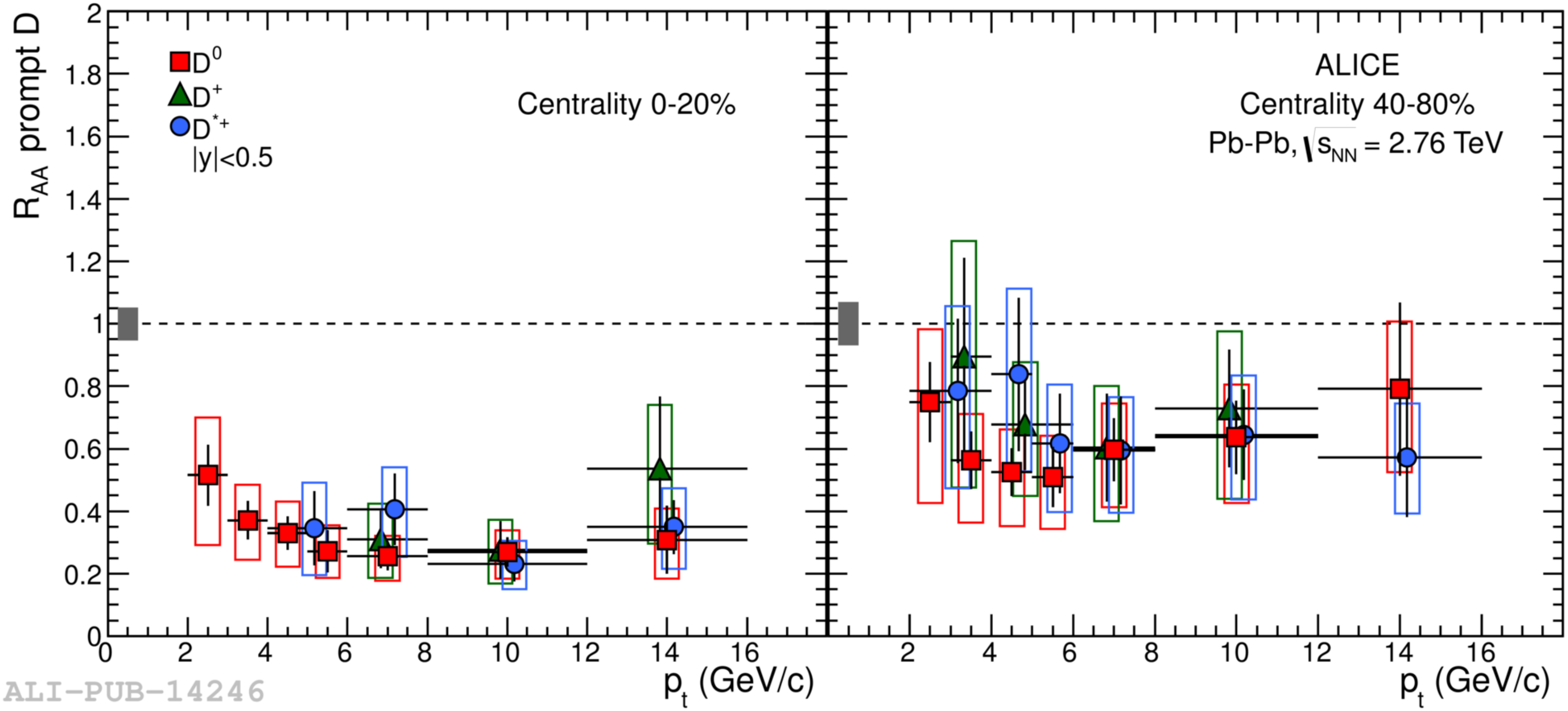
Heavy Quarks in the QGP

What is the mass dependence of jet quenching?



Do heavy quarks (c,b) flow with the QGP?

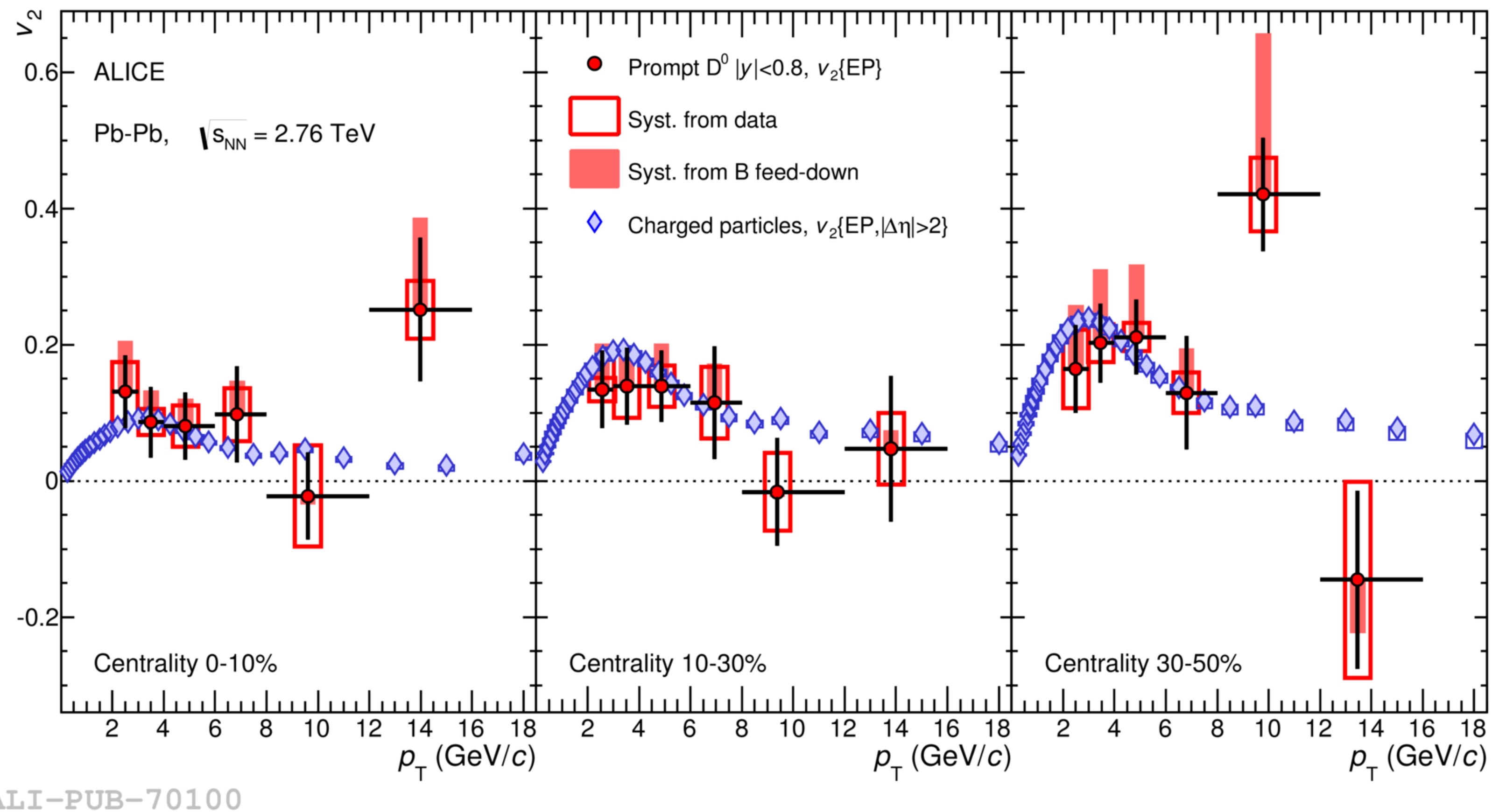
D-Meson Nuclear Modification Factor



D meson R_{AA} (0.3 for central collisions) slightly higher than for charged hadrons (0.15)

→ considerable energy loss

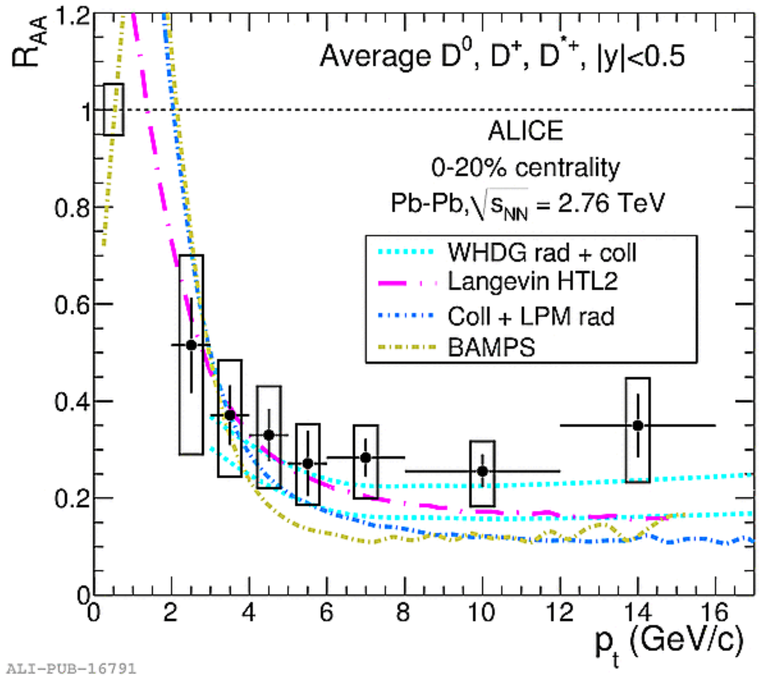
D-Meson Anisotropy

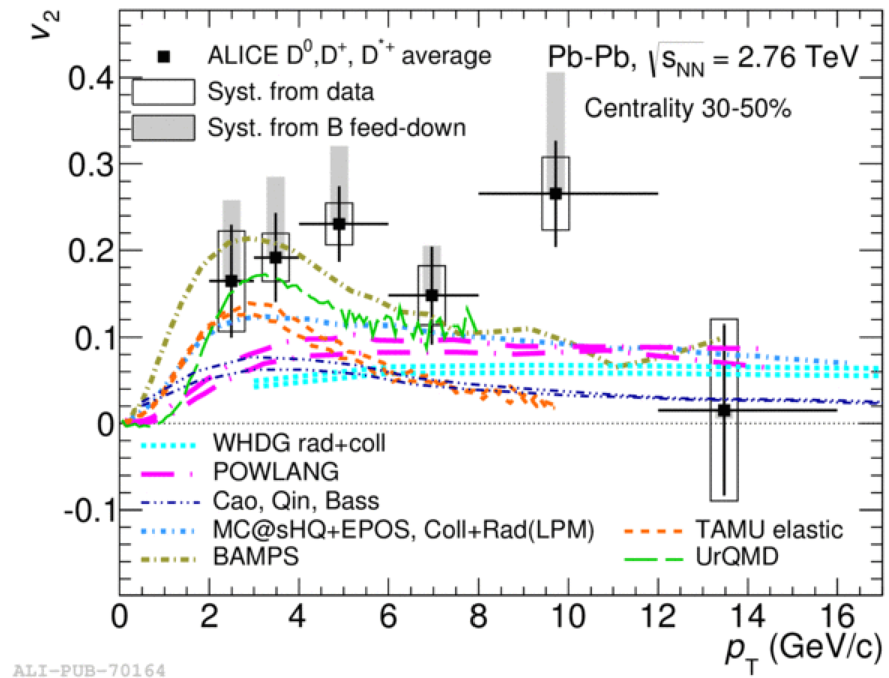


significant anisotropy!

→ heavy charm quarks participate in hydro expansion

Model Comparison





Extensive model comparison

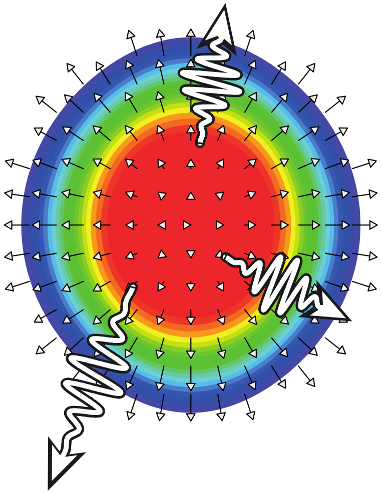
- no simultaneous description of R_{AA} and v_2
- theoretical and experimental improvements necessary!

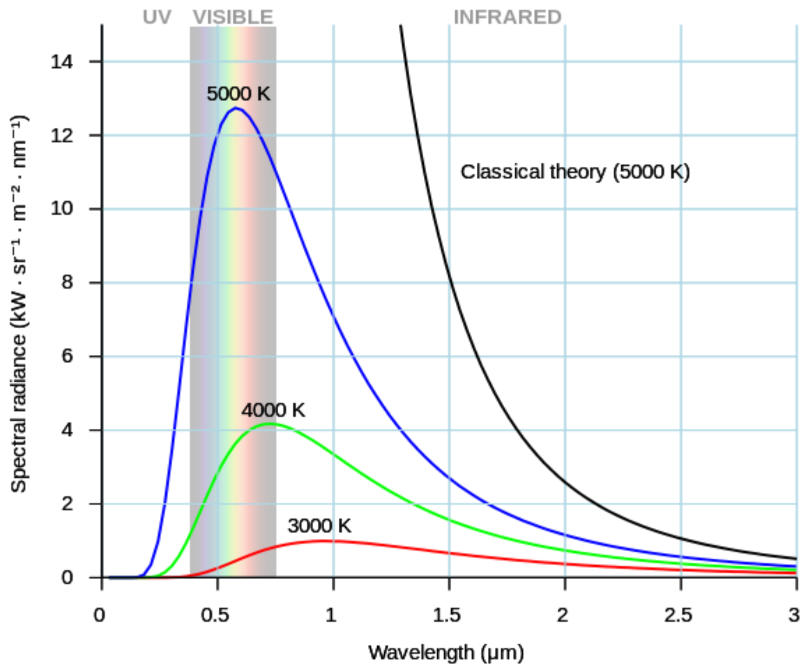
Thermal Photons

Planck's law and approximation for high photon energies

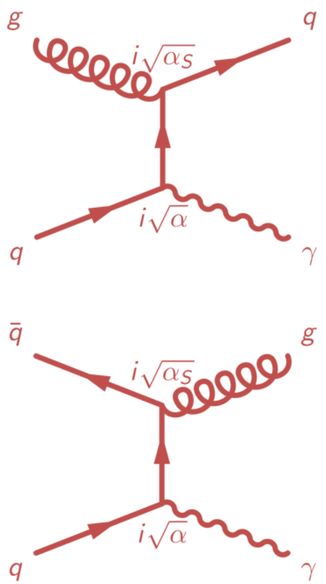
$$I \sim E_\gamma^3 \frac{1}{e^{E_\gamma/k_B T} - 1} \xrightarrow{E_\gamma \gg k_B T} I \sim e^{-E_\gamma/k_B T}$$

- measure temperature via thermal photons
- in analogy to IR thermometer and thermal imaging
- complicated by expansion of source

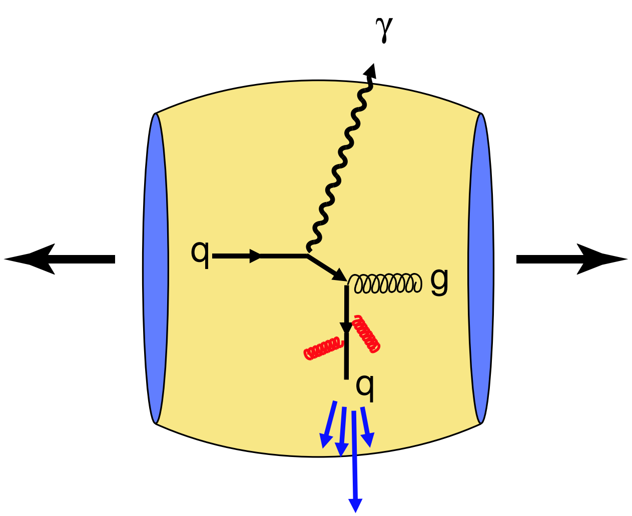


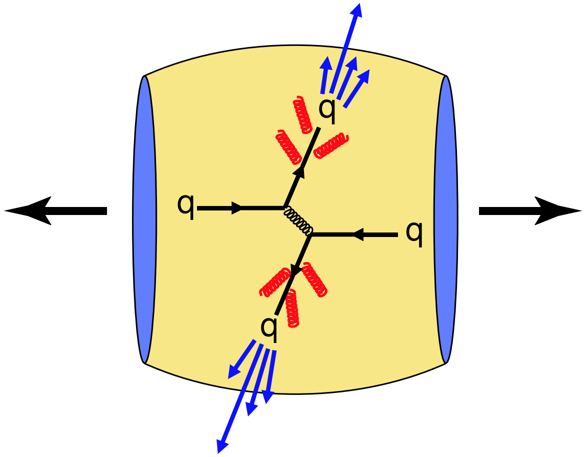


Photons from Hard Processes

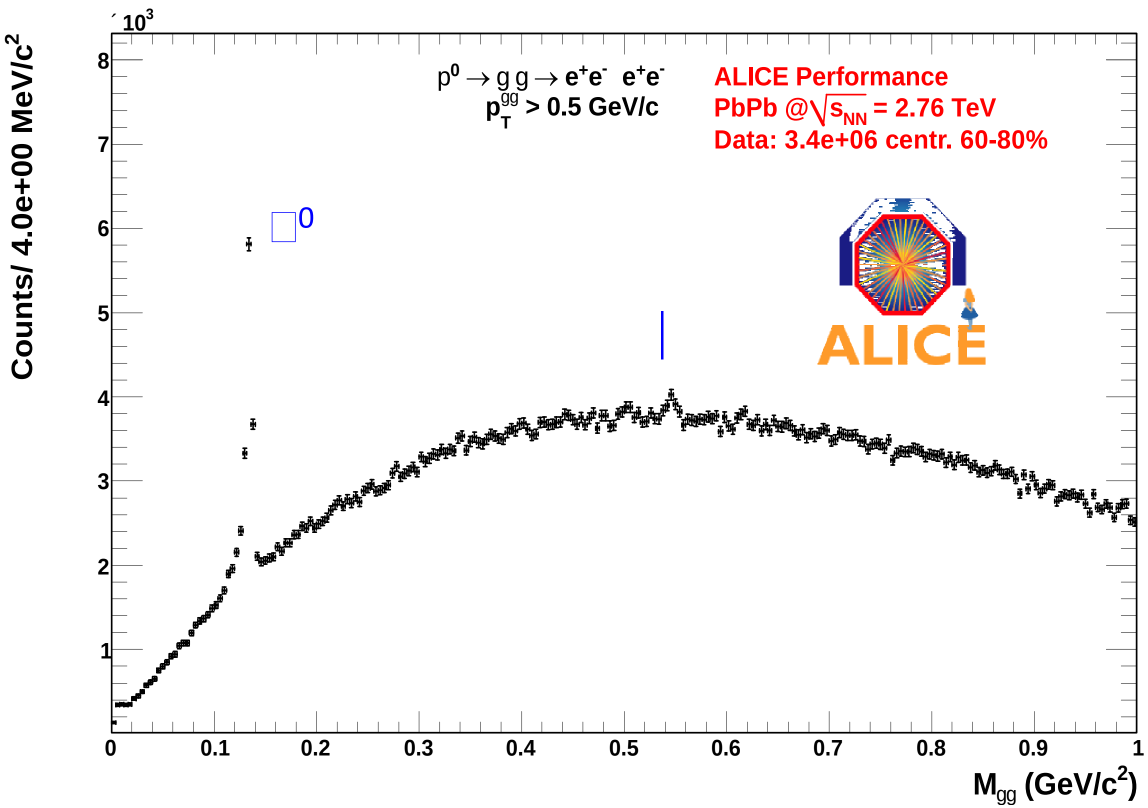


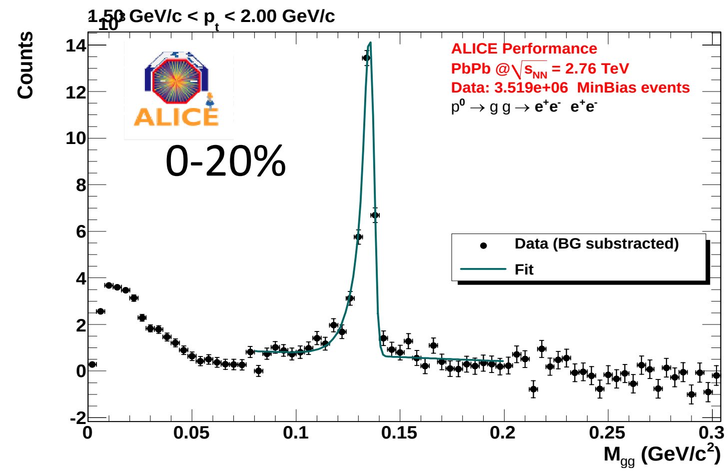
- creation in hard initial scatterings: same for pp, pA, AA
- photons escape QGP without interaction
- ideal reference for hard processes: comparison of jets and photons

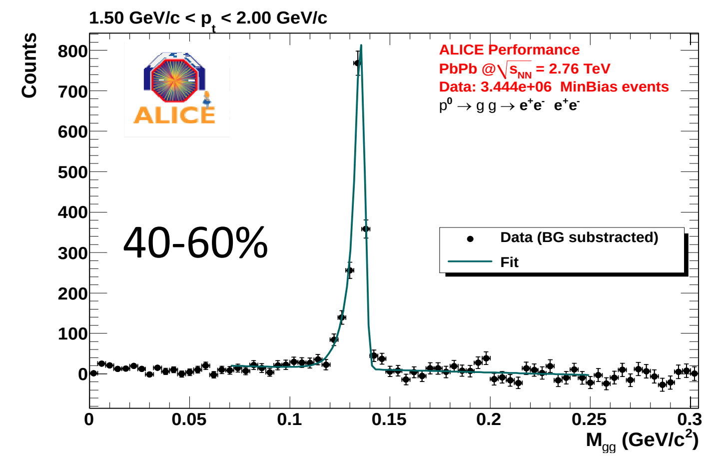




Background: Meson Decays

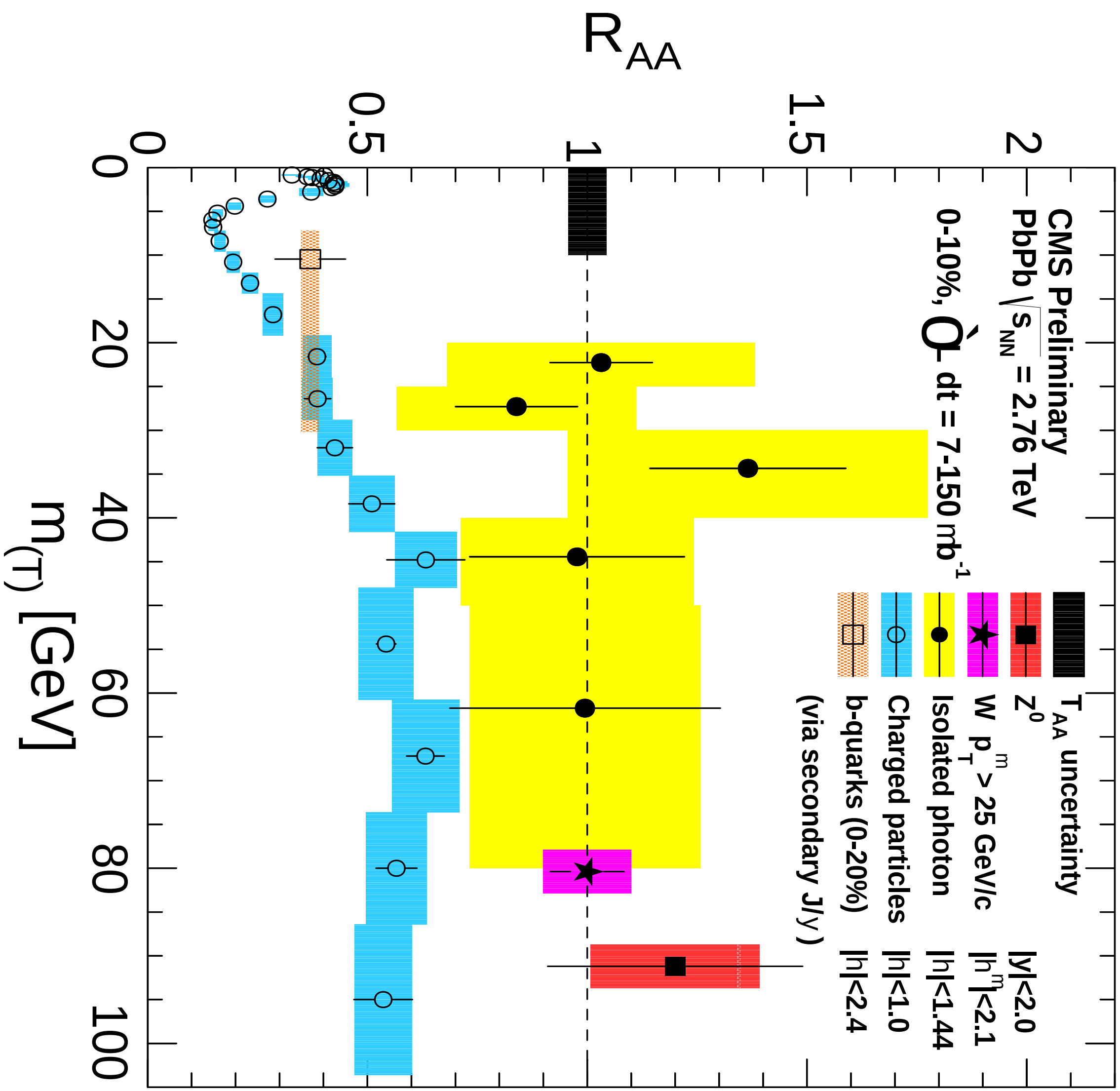






Good invariant mass resolution
even in Pb-Pb collisions

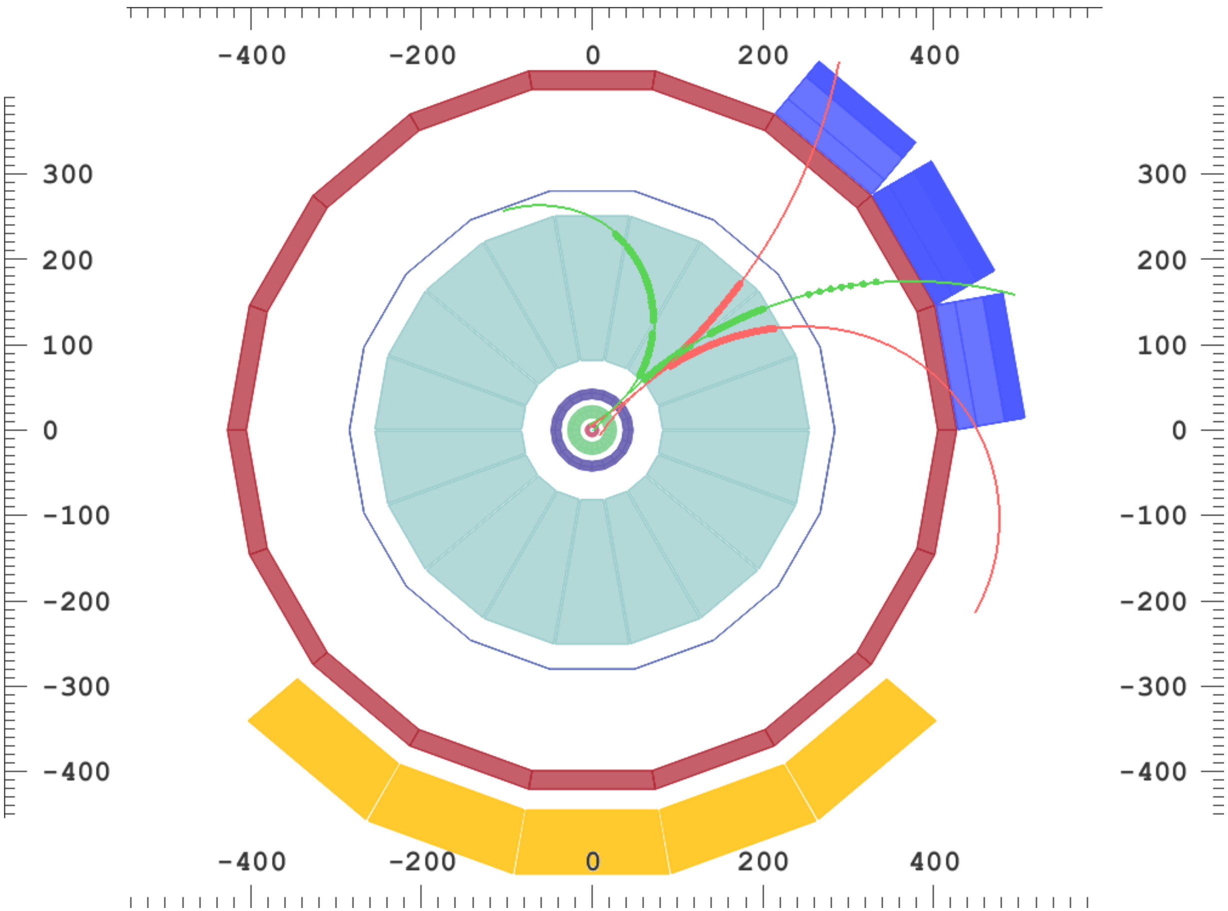
Isolated Photon R_{AA} by CMS



unmodified photon production at high p_T

- prompt photons
- hadron suppression is final state effect → energy loss

Photons at low p_T: Conversions



Photon conversions
$\gamma \rightarrow e^+e^-$
in detector material

- low conversion probability≈8.5%

π^0,η reconstruction with 2 conversions

- low efficiency
- good momentum resolution at low p_T

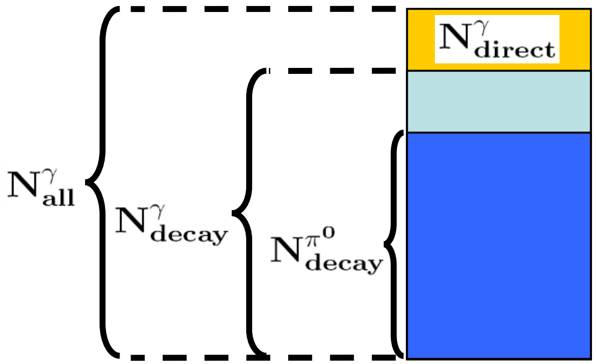
Direct Photon Measurement

Inclusive photons

$N_{incl} = N_{direct} + N_{decay}$

Need to separate signal from background

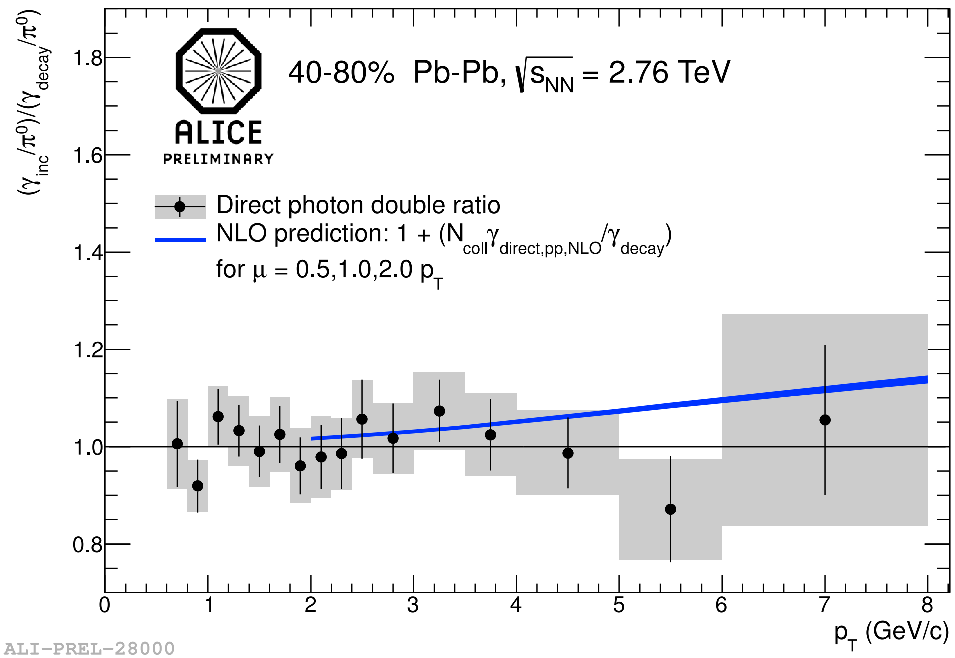
decay photons: $\pi^0, \eta \rightarrow \gamma\gamma$



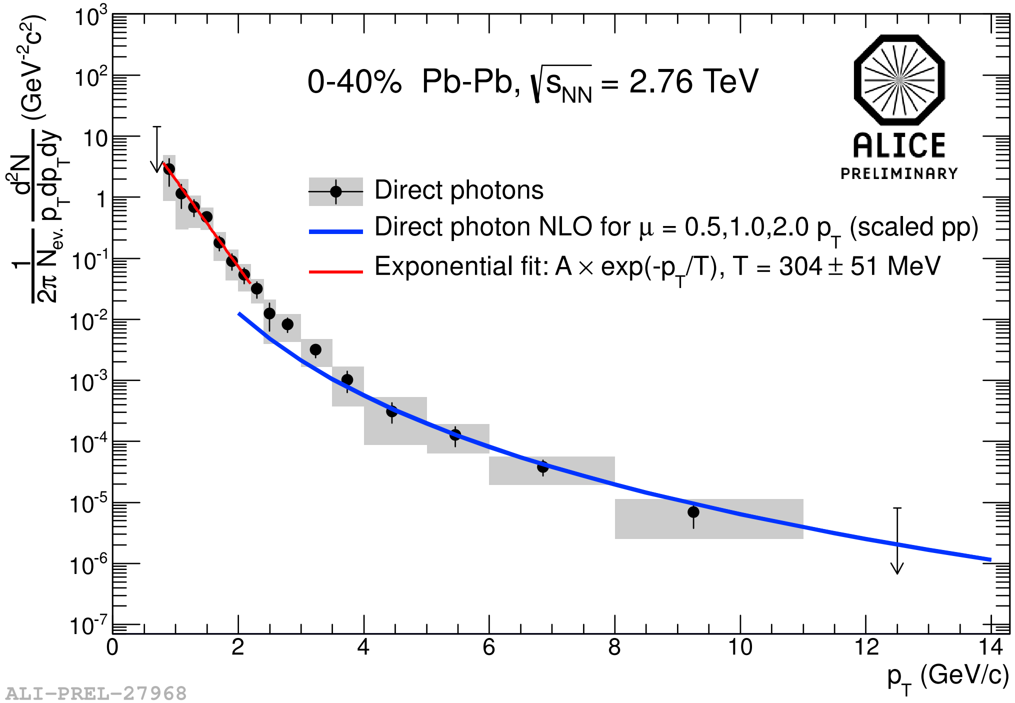
Statistical separation

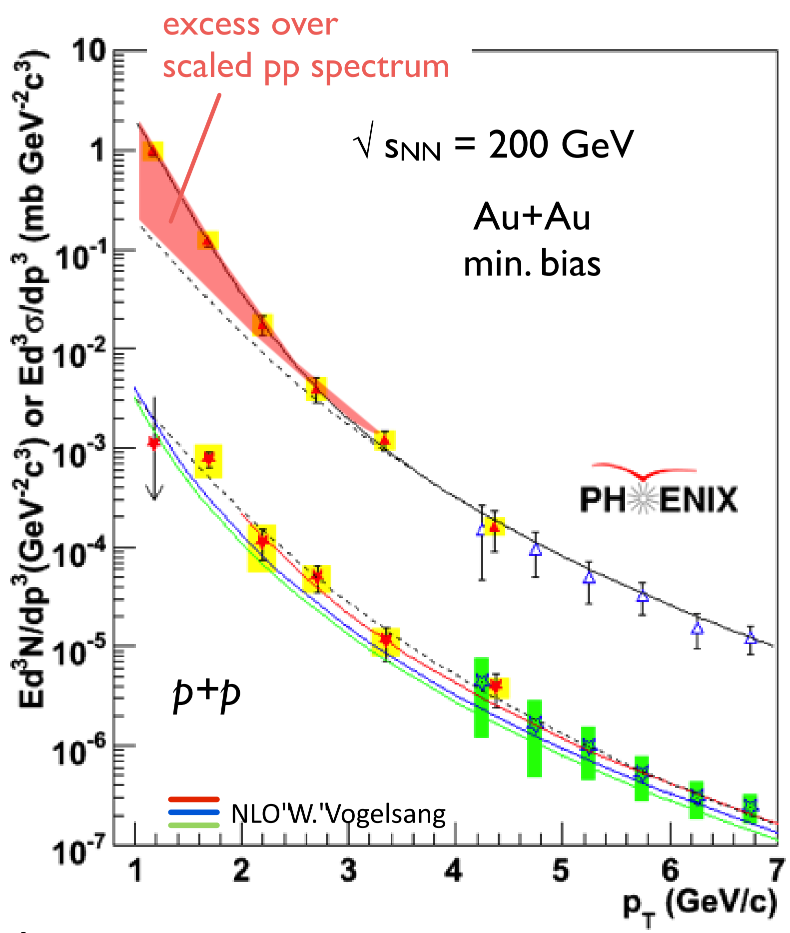
$N_{direct} = N_{incl} - N_{decay}$

- problem:
  - small signal
  - large uncertainties
- trick
  - measurement via N_{incl} / N_{decay}
  - cancellation of uncertainties



Direct Photon Spectra



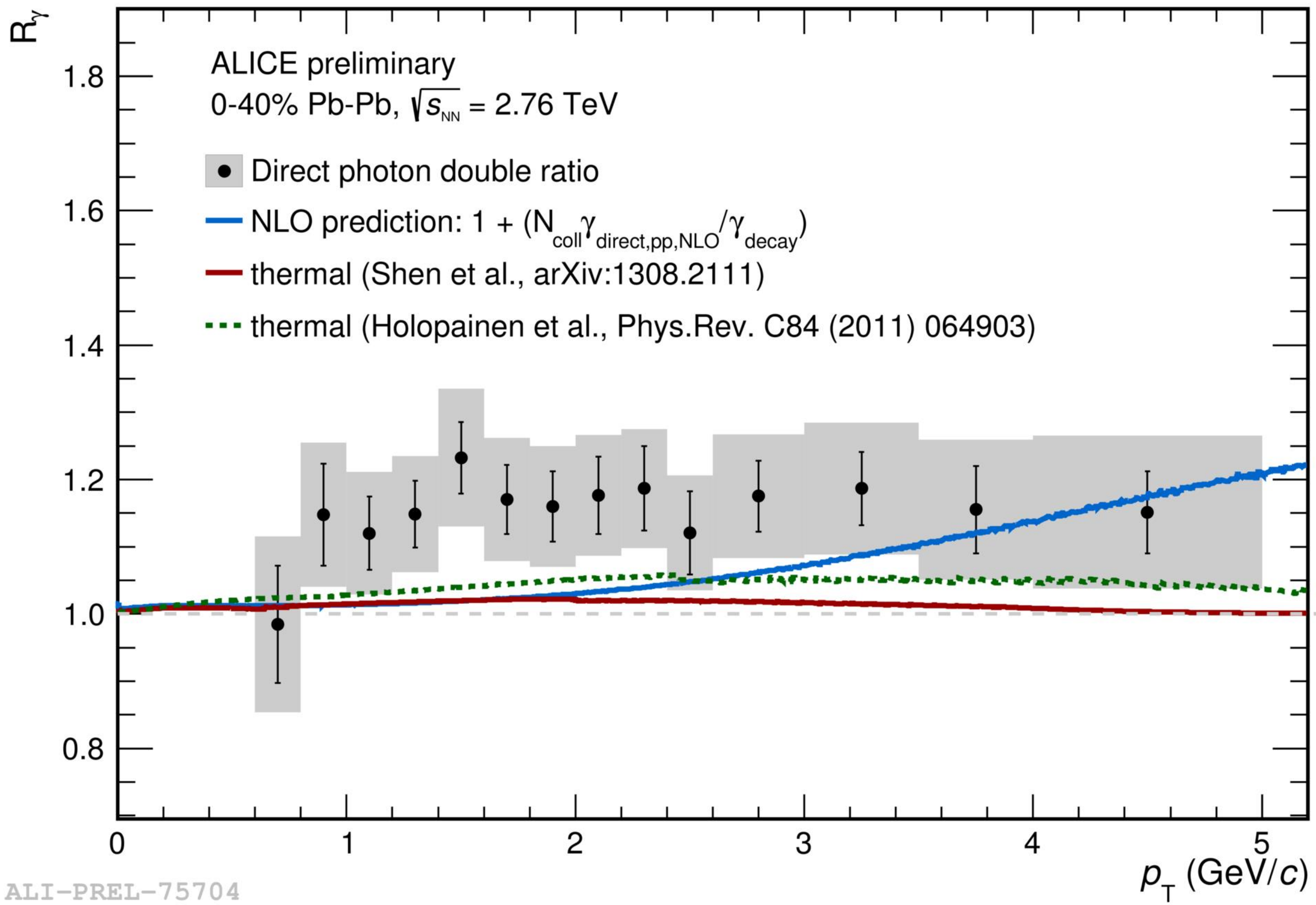


high p_T: prompt (NLO) photons

low p_T: direct photon excess, exponential slope

- slope parameter: 221 ± 28 MeV (PHENIX), 304 ± 51 MeV (ALICE
- thermal photons?

Comparison with Theory



disagreement between theory and experiment

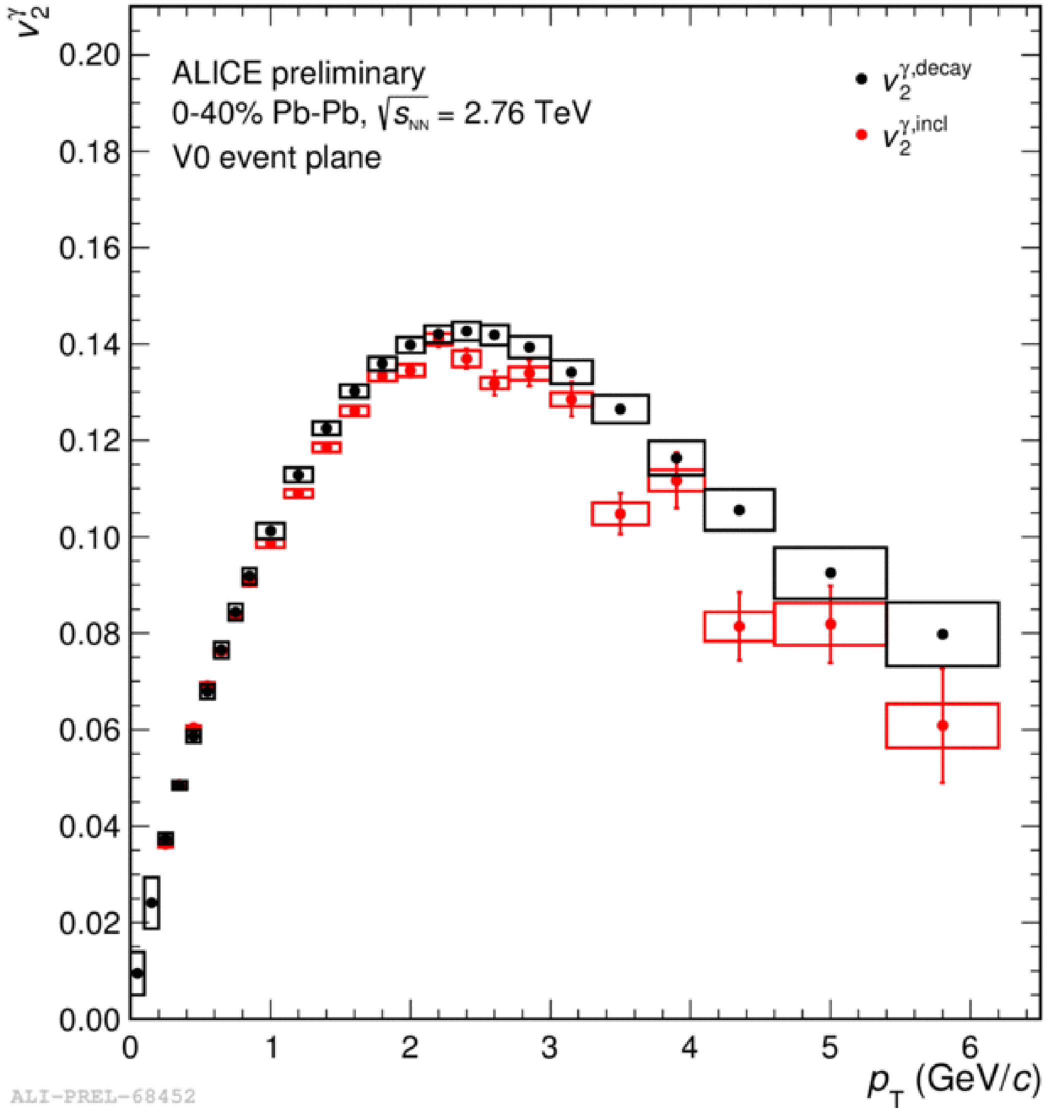
Photon v_2

Flow depends on photon source:

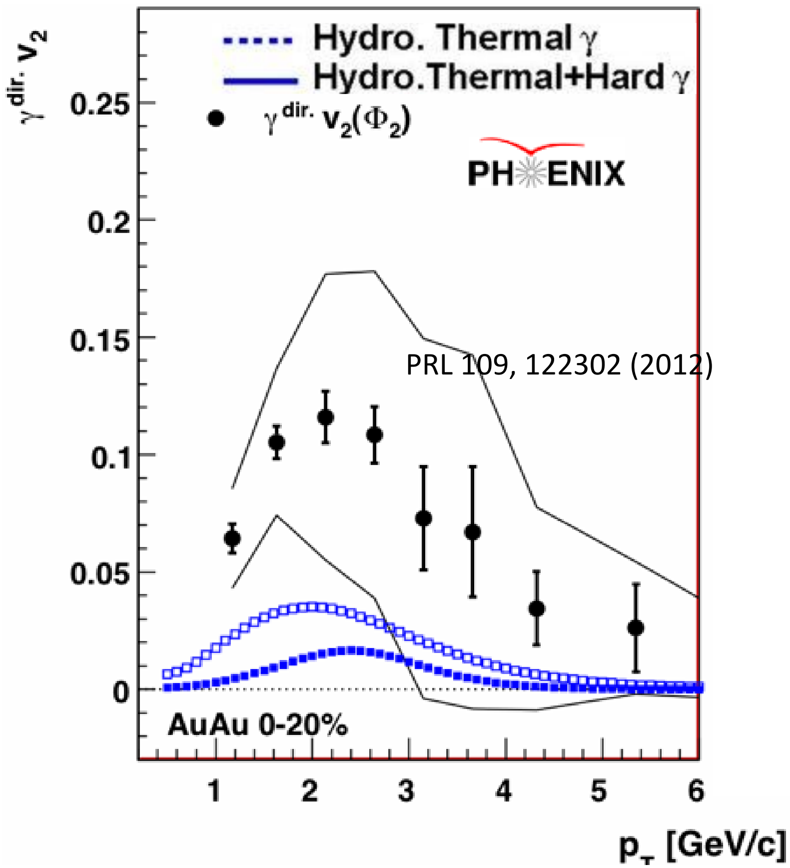
- thermal: emitted by flowing medium
- prompt: isotropic
- decay photons: follows from pion flow

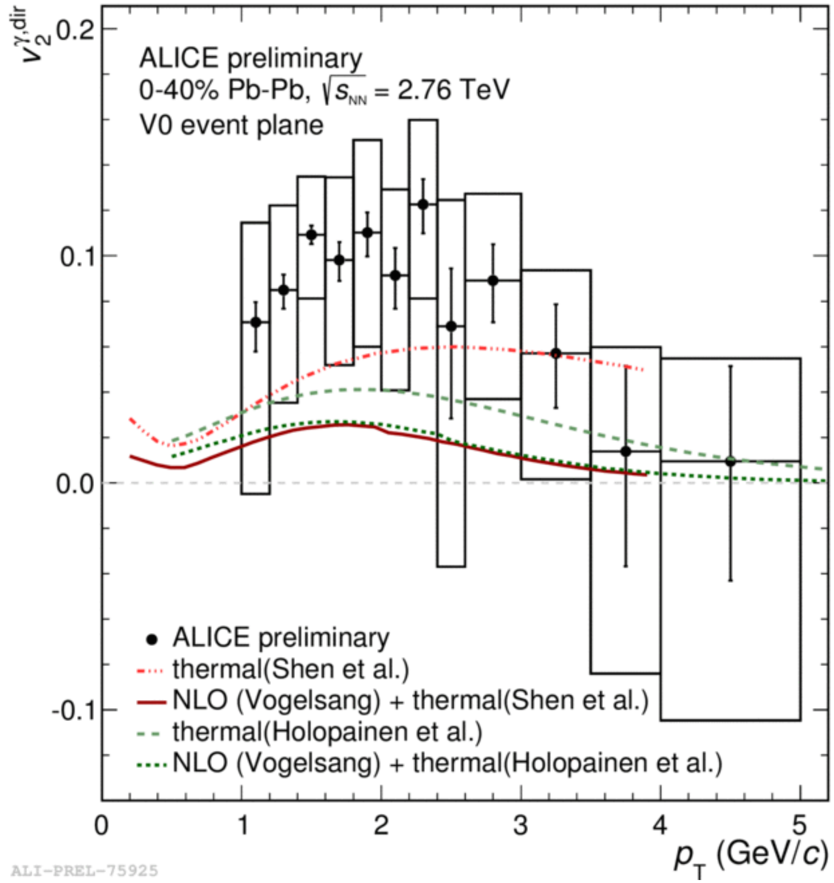
What do we expect?

- early emission
  → high temperature
  → small anisotropy
- late emission
  → low temperature
  → large anisotropy



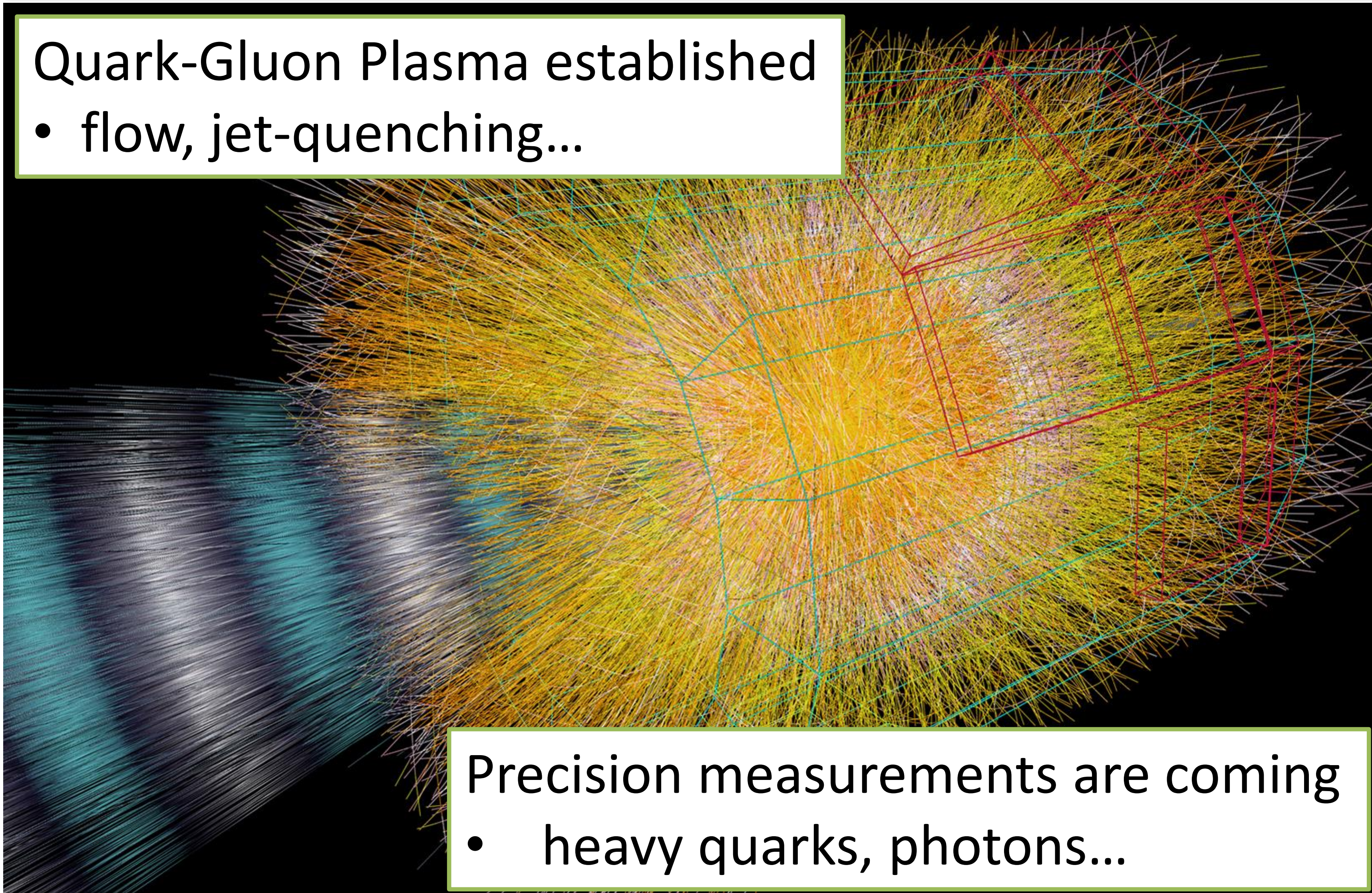
Direct Photon Anisotropy





Large flow signal, not reproduced by models
Do we understand photon production?

Summary & Outlook



Quark-Gluon Plasma established
- flow, jet-quenching…

Precision measurements are coming
- heavy quarks, photons…